The new frontiers of Composite Higgs Models at current and future colliders

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@ Top LHC France 2023,
Strasbourg

Motivation

- Composite models 'solve' the Hierarchy problem...
- with new scale in the multi-TeV!

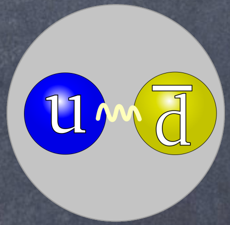
multi-TeV mountain

- What are we looking for?

  -> Precision EW + Higgs observables
  -> light composite scalars
  -> multi-TeV resonances (top partners, pNGBs, spin-1)

Composite Higgs models 101

- Symmetry broken by a condensate (of TC-fermions)
- Higgs and longitudinal Z/W emerge as mesons (pions)



Scales:

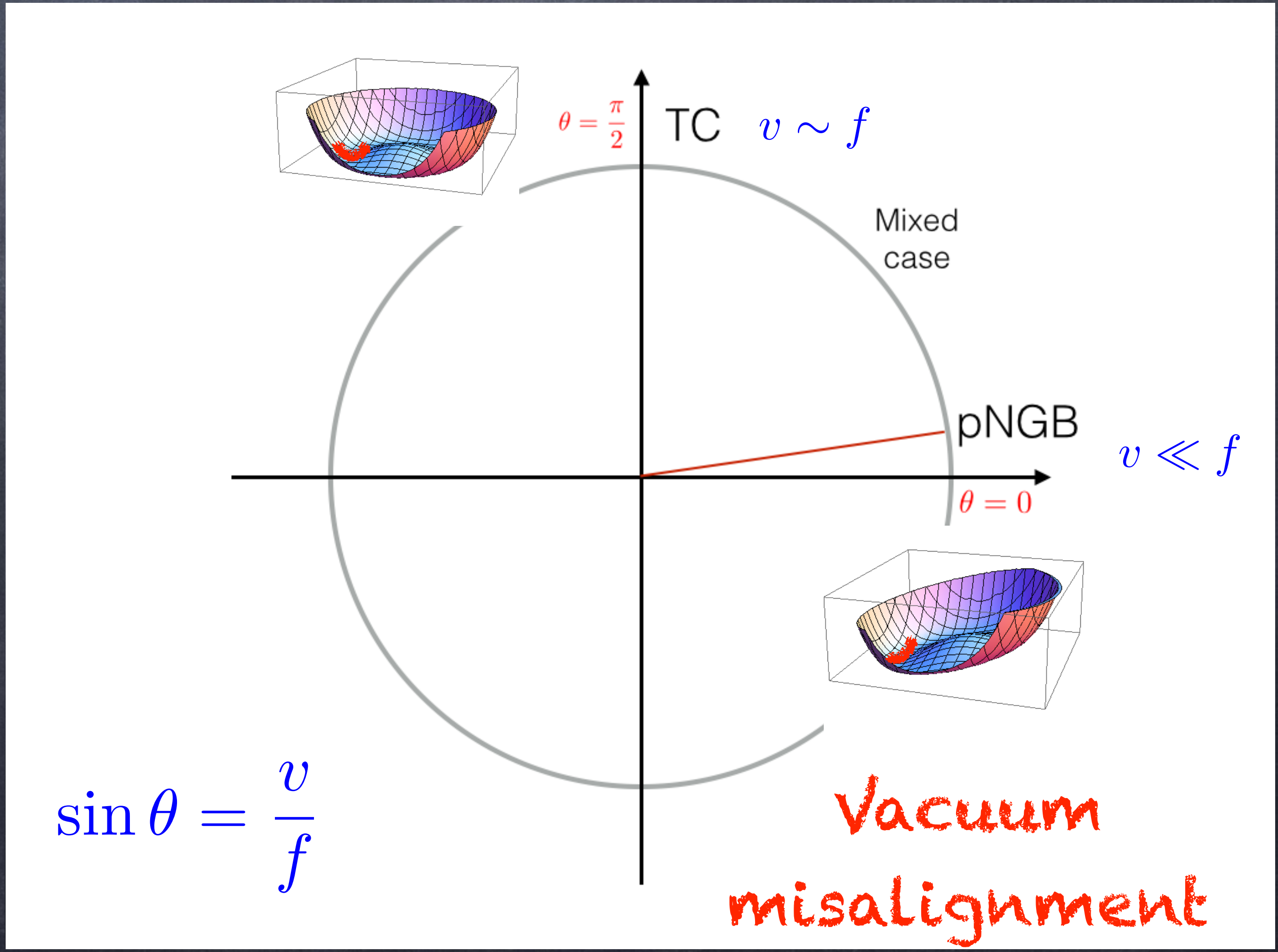
f : Higgs decay constant

v : EW scale

$$m_\rho \sim 4\pi f$$

EWPTs + Higgs coupl. limit:

$$\boxed{f \gtrsim 4v \sim 1\ \text{TeV}}$$



$$\sin\theta = \frac{v}{f}$$

Vacuum misalignment

Composite Higgs models 101

How can light states emerge?

	Top loops 	Gauge loops 	TC-fermion masses 
ϕ	$\sim y_t^2 f^2$	$\sim g^2 f^2$	$\sim m_\psi f$
h (h massless for vanishing v)	$\sim y_t^2 f^2 s_\theta^2 = y_t^2 v^2$	$\sim g^2 f^2 s_\theta^2 = g^2 v^2$	X
a	X	X	$\sim m_\psi f$ This can be small!

The partial compositeness paradigm

Kaplan Nucl.Phys. B365 (1991) 259

$$\frac{1}{\Lambda_{\text{fl.}}^{d-1}} \mathcal{O}_H q_L^c q_R \qquad \Delta m_H^2 \sim \left(\frac{4\pi f}{\Lambda_{\text{fl.}}}\right)^{d-4} f^2$$

Both irrelevant if

we assume: $d_H > 1$ $d_{H^2} > 4$

Let's postulate the existence of fermionic operators:

$$\frac{1}{\Lambda_{\text{fl.}}^{d_F-5/2}} \left(\tilde{y}_L \; q_L \mathcal{F}_L + \tilde{y}_R \; q_R \mathcal{F}_R\right)$$

This dimension is not related to the Higgs!

$$\Downarrow$$

$$f\left(y_L \; q_L Q_L + y_R \; q_R Q_R\right) \quad \text{with} \quad y_{L/R} f \sim \left(\frac{4\pi f}{\Lambda_{\text{fl.}}}\right)^{d_F-5/2} 4\pi f$$

Sequestering QCD in Partial compositeness

G.Ferretti, D.Karateev
1312.5330, 1604.06467

$\mathcal{G}_{\mathrm{TC}}$: rep R rep R′

Q χ

$T' = QQ\chi$ or $Q\chi\chi$

SM : EW colour + hypercharge

global : $\langle QQ \rangle \neq 0$

↓

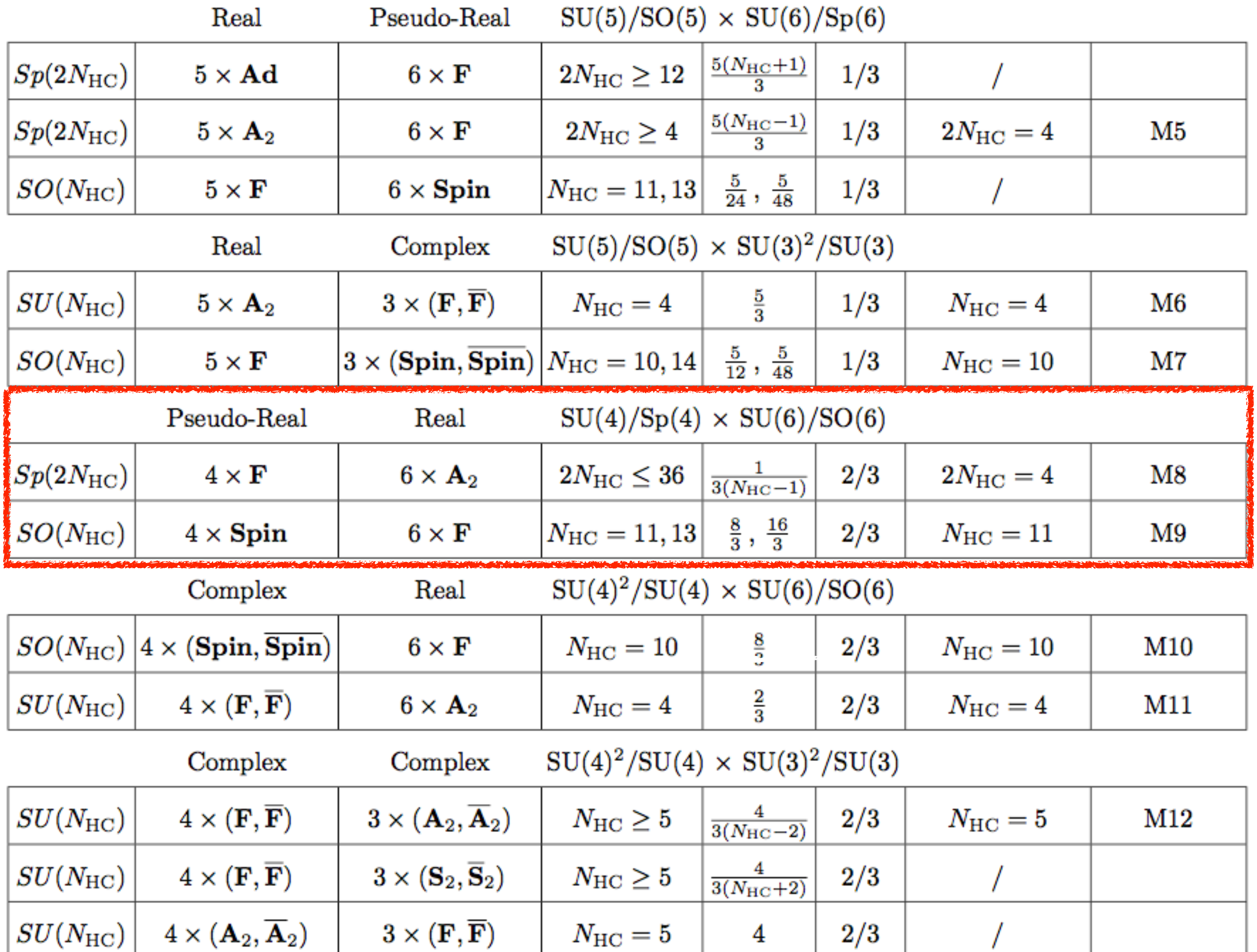
pNGB Higgs
DM?

a) $\langle \chi\chi \rangle \neq 0$

coloured pNGBs
di-boson

b) $\langle \chi\chi \rangle = 0$

light top partners
from t Hooft anomaly
conditions?



	Real	Pseudo-Real	SU(5)/SO(5) × SU(6)/Sp(6)				
$Sp(2N_{\rm HC})$	$5\times\mathbf{Ad}$	$6\times\mathbf{F}$	$2N_{\rm HC}\geq 12$	$\frac{5(N_{\rm HC}+1)}{3}$	$1/3$	/	
$Sp(2N_{\rm HC})$	$5\times\mathbf{A}_2$	$6\times\mathbf{F}$	$2N_{\rm HC}\geq 4$	$\frac{5(N_{\rm HC}-1)}{3}$	$1/3$	$2N_{\rm HC}=4$	M5
$SO(N_{\rm HC})$	$5\times\mathbf{F}$	$6\times\mathbf{Spin}$	$N_{\rm HC}=11,13$	$\frac{5}{24}$, $\frac{5}{48}$	$1/3$	/	
	Real	Complex	SU(5)/SO(5) × SU(3)^2/SU(3)				
$SU(N_{\rm HC})$	$5\times\mathbf{A}_2$	$3\times(\mathbf{F},\overline{\mathbf{F}})$	$N_{\rm HC}=4$	$\frac{5}{3}$	$1/3$	$N_{\rm HC}=4$	M6
$SO(N_{\rm HC})$	$5\times\mathbf{F}$	$3\times(\mathbf{Spin},\overline{\mathbf{Spin}})$	$N_{\rm HC}=10,14$	$\frac{5}{12}$, $\frac{5}{48}$	$1/3$	$N_{\rm HC}=10$	M7
	Pseudo-Real	Real	SU(4)/Sp(4) × SU(6)/SO(6)				
$Sp(2N_{\rm HC})$	$4\times\mathbf{F}$	$6\times\mathbf{A}_2$	$2N_{\rm HC}\leq 36$	$\frac{1}{3(N_{\rm HC}-1)}$	$2/3$	$2N_{\rm HC}=4$	M8
$SO(N_{\rm HC})$	$4\times\mathbf{Spin}$	$6\times\mathbf{F}$	$N_{\rm HC}=11,13$	$\frac{8}{3}$, $\frac{16}{3}$	$2/3$	$N_{\rm HC}=11$	M9
	Complex	Real	SU(4)^2/SU(4) × SU(6)/SO(6)				
$SO(N_{\rm HC})$	$4\times(\mathbf{Spin},\overline{\mathbf{Spin}})$	$6\times\mathbf{F}$	$N_{\rm HC}=10$	$\frac{8}{3}$	$2/3$	$N_{\rm HC}=10$	M10
$SU(N_{\rm HC})$	$4\times(\mathbf{F},\overline{\mathbf{F}})$	$6\times\mathbf{A}_2$	$N_{\rm HC}=4$	$\frac{2}{3}$	$2/3$	$N_{\rm HC}=4$	M11
	Complex	Complex	SU(4)^2/SU(4) × SU(3)^2/SU(3)				
$SU(N_{\rm HC})$	$4\times(\mathbf{F},\overline{\mathbf{F}})$	$3\times(\mathbf{A}_2,\overline{\mathbf{A}}_2)$	$N_{\rm HC}\geq 5$	$\frac{4}{3(N_{\rm HC}-2)}$	$2/3$	$N_{\rm HC}=5$	M12
$SU(N_{\rm HC})$	$4\times(\mathbf{F},\overline{\mathbf{F}})$	$3\times(\mathbf{S}_2,\overline{\mathbf{S}}_2)$	$N_{\rm HC}\geq 5$	$\frac{4}{3(N_{\rm HC}+2)}$	$2/3$	/	
$SU(N_{\rm HC})$	$4\times(\mathbf{A}_2,\overline{\mathbf{A}}_2)$	$3\times(\mathbf{F},\overline{\mathbf{F}})$	$N_{\rm HC}=5$	4	$2/3$	/	

Composite models at various scales

G.C., S.Vatani, C.Zhang
1911.05454, 2005.12302

Condensation scale

Usual low energy description
of composite Higgs models

Standard Model

One of Ferretti
models

Composite models at various scales

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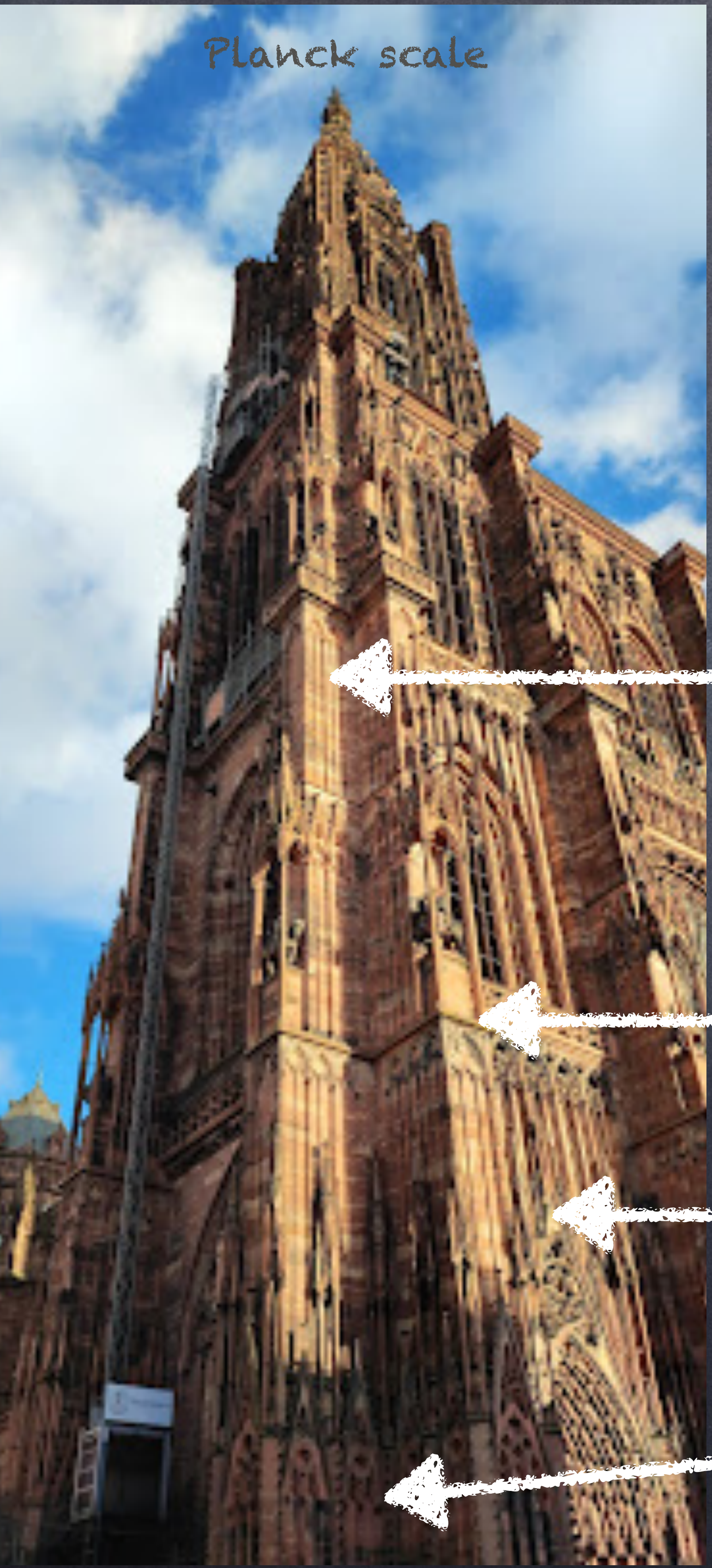

Conformal window
(large scaling dimensions)

One of Ferretti
models +
additional fermions

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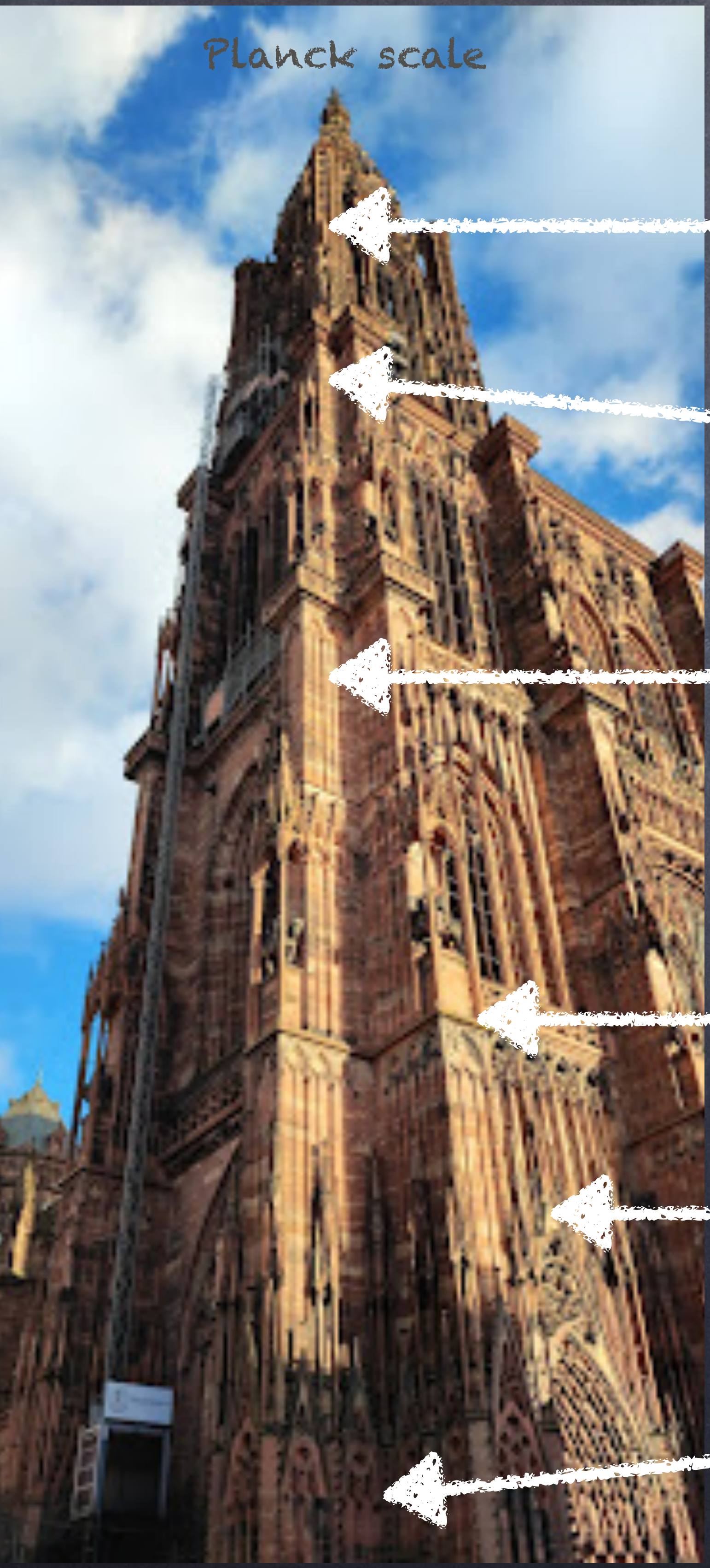
Composite models at various scales



G.C., S.Vatani, C.Zhang
1911.05454, 2005.12302

HC and SM gauge groups partially unified

Symmetry breaking by scalars — 4-fermion Ops generated!

Conformal window (large scaling dimensions) — One of Ferretti models + additional fermions

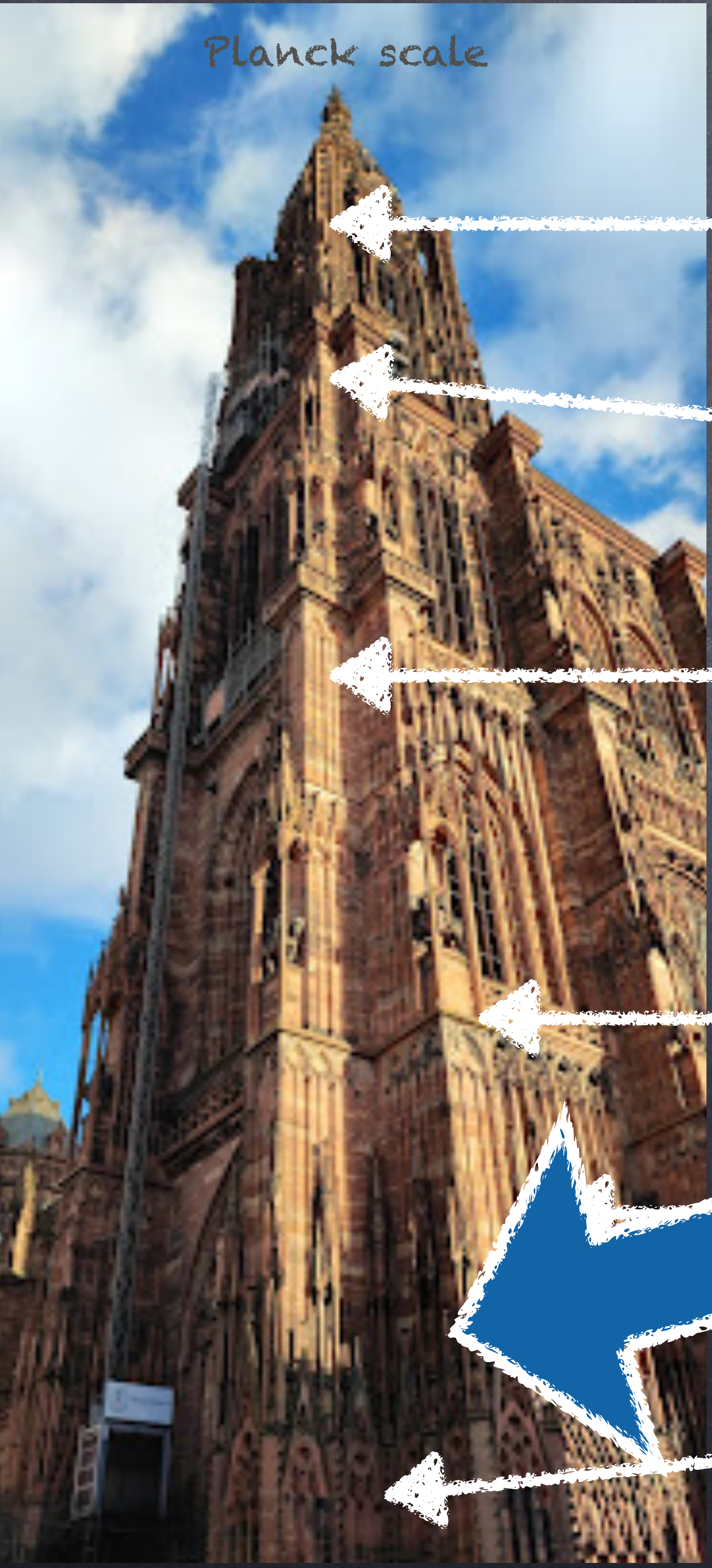
Condensation scale

Usual low energy description of composite Higgs models

Standard Model

One of Ferretti models

Composite models at various scales



HC and SM gauge
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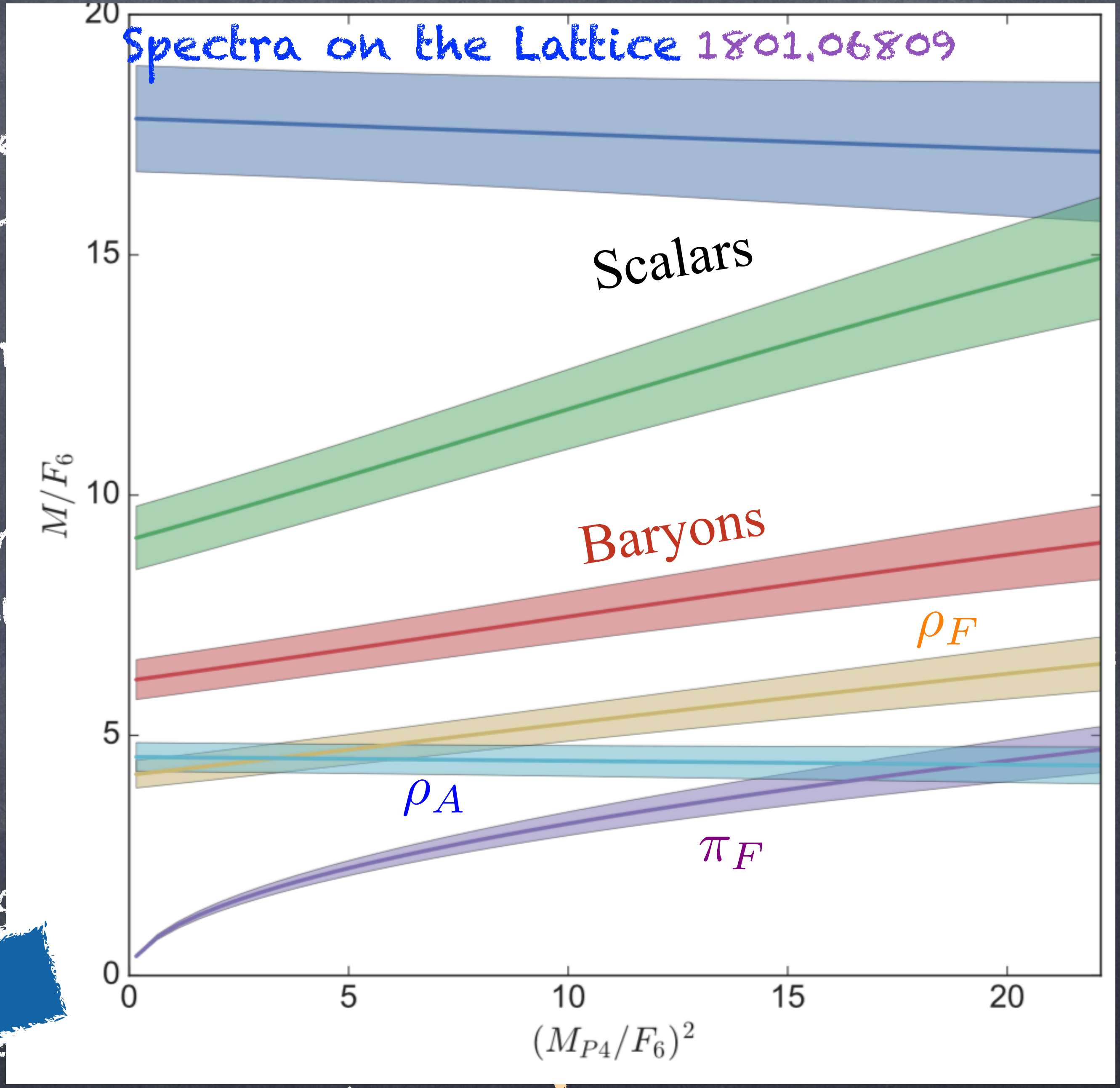
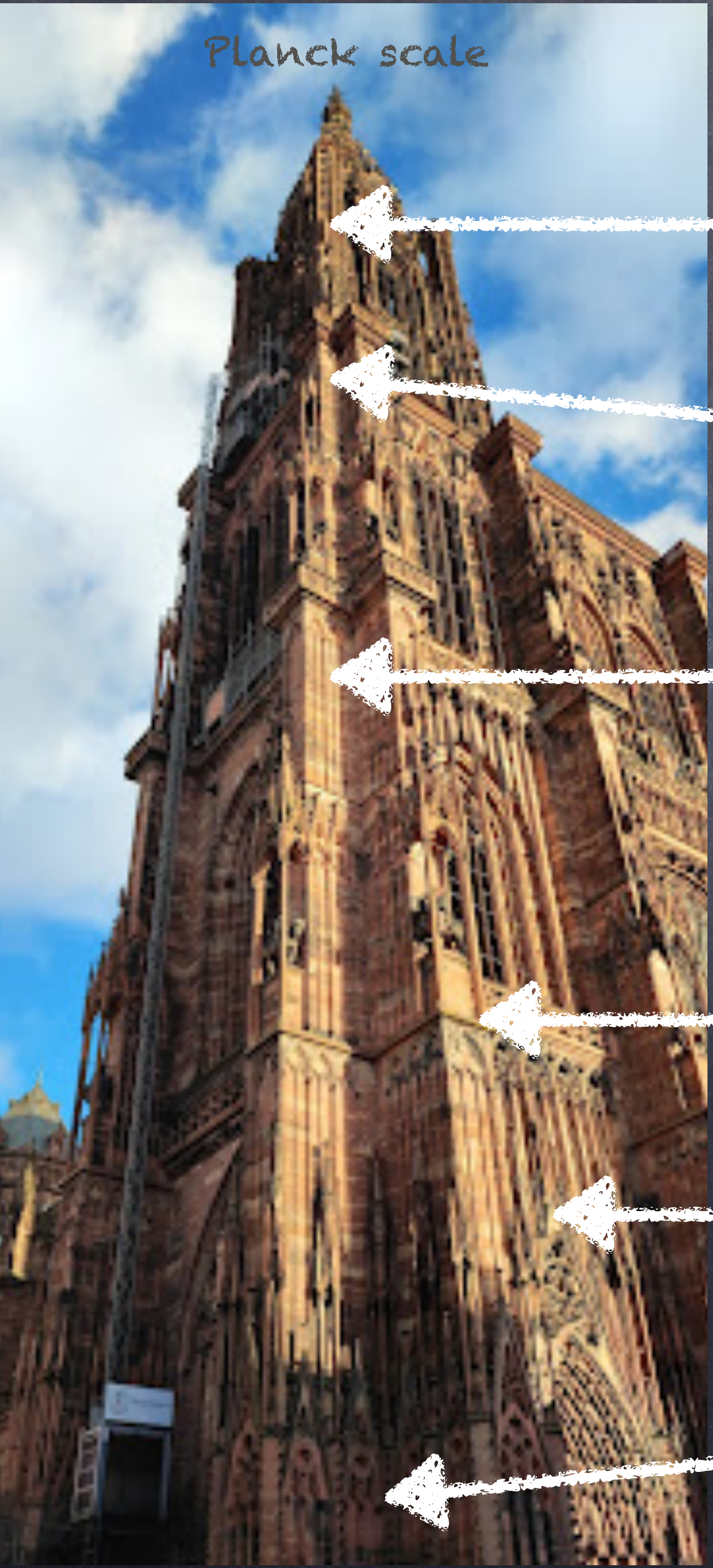
models

Standard Model


Spectra on the Lattice 1801.06809

Composite models at various scales



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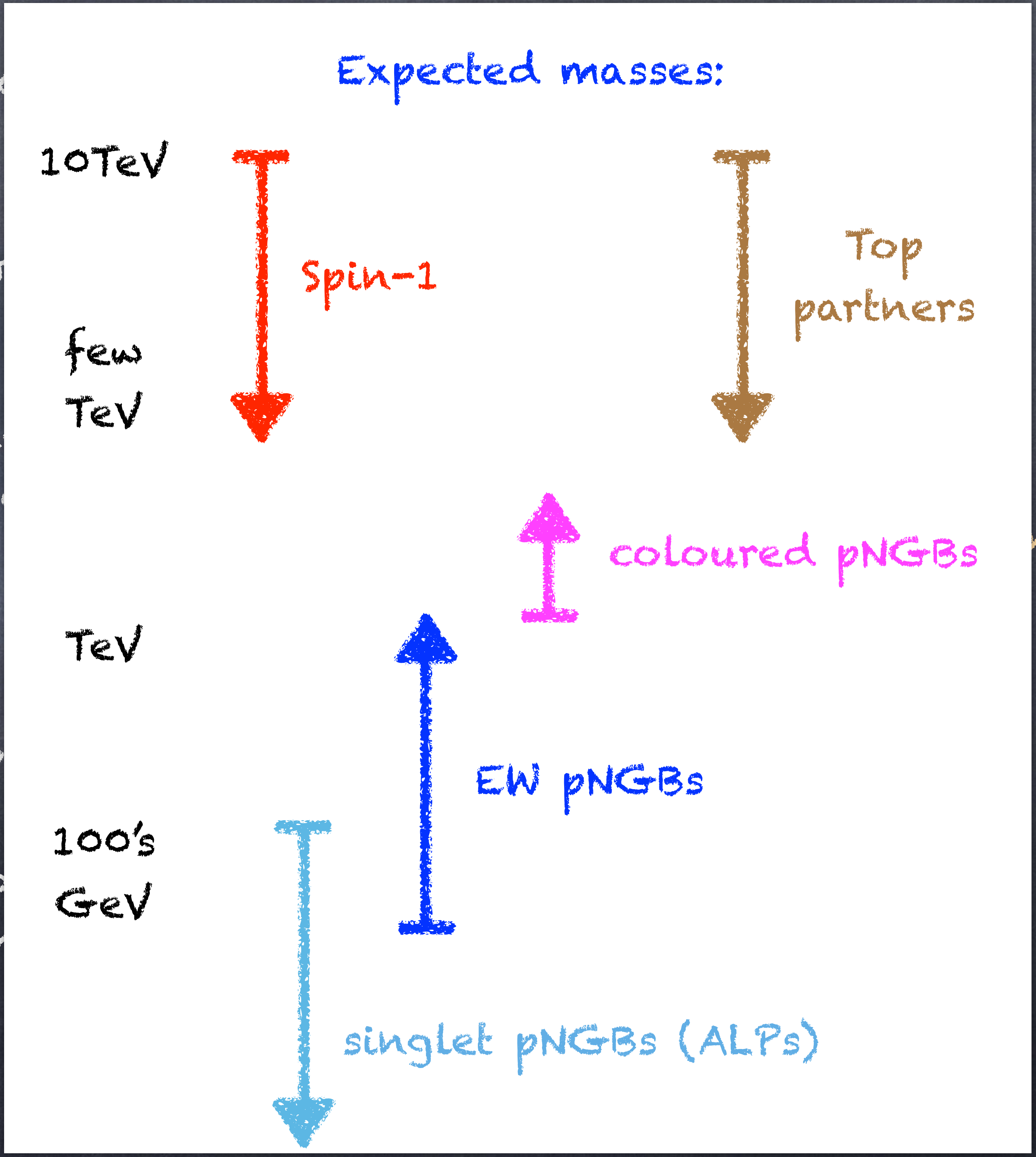

Expected masses:

The composite Higgs wilderness

- Light ALPs
- Electroweak pNGBs
- Coloured scalars
- Common exotic top partner decays
- Exotic top partners
- Spin-1 resonances (in progress)
- What are low-energy anomalies trying to tell us?

The composite Higgs wilderness

EW and Higgs precision!!!

- Light ALPs
- Electroweak pNGBs
- Coloured scalars
- Common exotic top partner decays
- Exotic top partners
- Spin-1 resonances (in progress)
- What are low-energy anomalies trying to tell us?

Typical ALP Lagrangian:

$$\mathcal{L}_{\text{eff}}^{D\leq 5} = \frac{1}{2}\,(\partial_\mu a)(\partial^\mu a) - \frac{m_{a,0}^2}{2}\,a^2 + \frac{\partial^\mu a}{\Lambda}\sum_F \bar{\psi}_F\,\boldsymbol{C}_F\,\gamma_\mu\,\psi_F$$
$$+\, g_s^2\,C_{GG}\,\frac{a}{\Lambda}\,G_{\mu\nu}^A\,\tilde{G}^{\mu\nu,A} + g^2\,C_{WW}\,\frac{a}{\Lambda}\,W_{\mu\nu}^A\,\tilde{W}^{\mu\nu,A} + g'^2\,C_{BB}\,\frac{a}{\Lambda}\,B_{\mu\nu}\,\tilde{B}^{\mu\nu}\,,$$

Composite Higgs scenario:

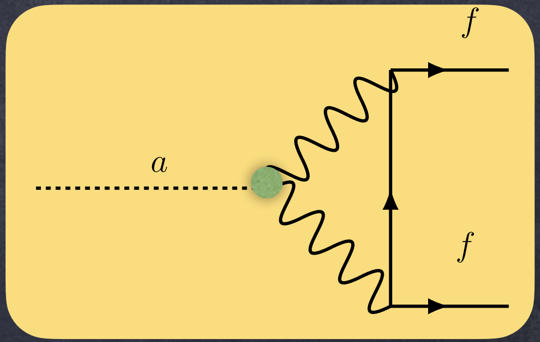
$$\frac{C_{WW}}{\Lambda} \sim \frac{C_{BB}}{\Lambda} \sim \frac{N_{\text{TC}}}{64\sqrt{2}\,\pi^2 f}$$

$$\frac{C_{GG}}{\Lambda} = 0$$

(Poor bounds at the LHC)

$$(C_{\gamma\gamma} = C_{WW} + C_{BB})$$

$\mathbf{C}_F$ is loop-induced:



M.Bauer et al, 1708.00443

Typical ALP Lagrangian:

$$\mathcal{L}_{\text{eff}}^{D\leq 5} = \frac{1}{2}\,(\partial_\mu a)(\partial^\mu a) - \frac{m_{a,0}^2}{2}\,a^2 + \frac{\partial^\mu a}{\Lambda}\sum_F \bar{\psi}_F\,\boldsymbol{C}_F\,\gamma_\mu\,\psi_F$$
$$+\, g_s^2\,C_{GG}\,\frac{a}{\Lambda}\,G_{\mu\nu}^A\,\tilde{G}^{\mu\nu,A} + g^2\,C_{WW}\,\frac{a}{\Lambda}\,W_{\mu\nu}^A\,\tilde{W}^{\mu\nu,A} + g'^2\,C_{BB}\,\frac{a}{\Lambda}\,B_{\mu\nu}\,\tilde{B}^{\mu\nu}\,,$$

Composite Higgs scenario:

$$\frac{C_{WW}}{\Lambda} \sim \frac{C_{BB}}{\Lambda} \sim \frac{N_{\text{TC}}}{64\sqrt{2}\,\pi^2 f}$$

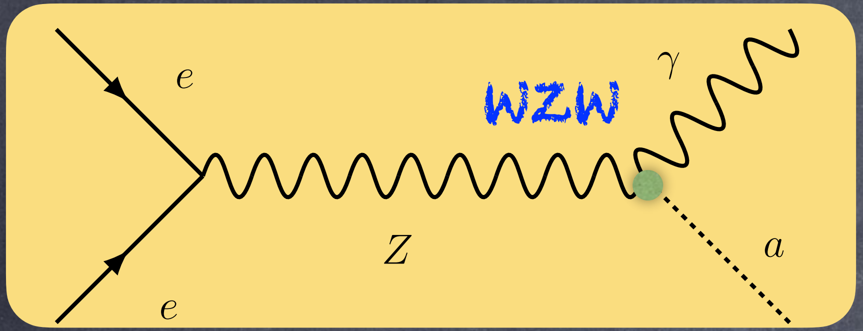
$$(C_{\gamma\gamma} = C_{WW} + C_{BB})$$

Free parameters:

f, m_a

We will consider two scenarios:
Photo-philic and
Photo-phobic

Tera-Z portal to compositeness (via ALPs)

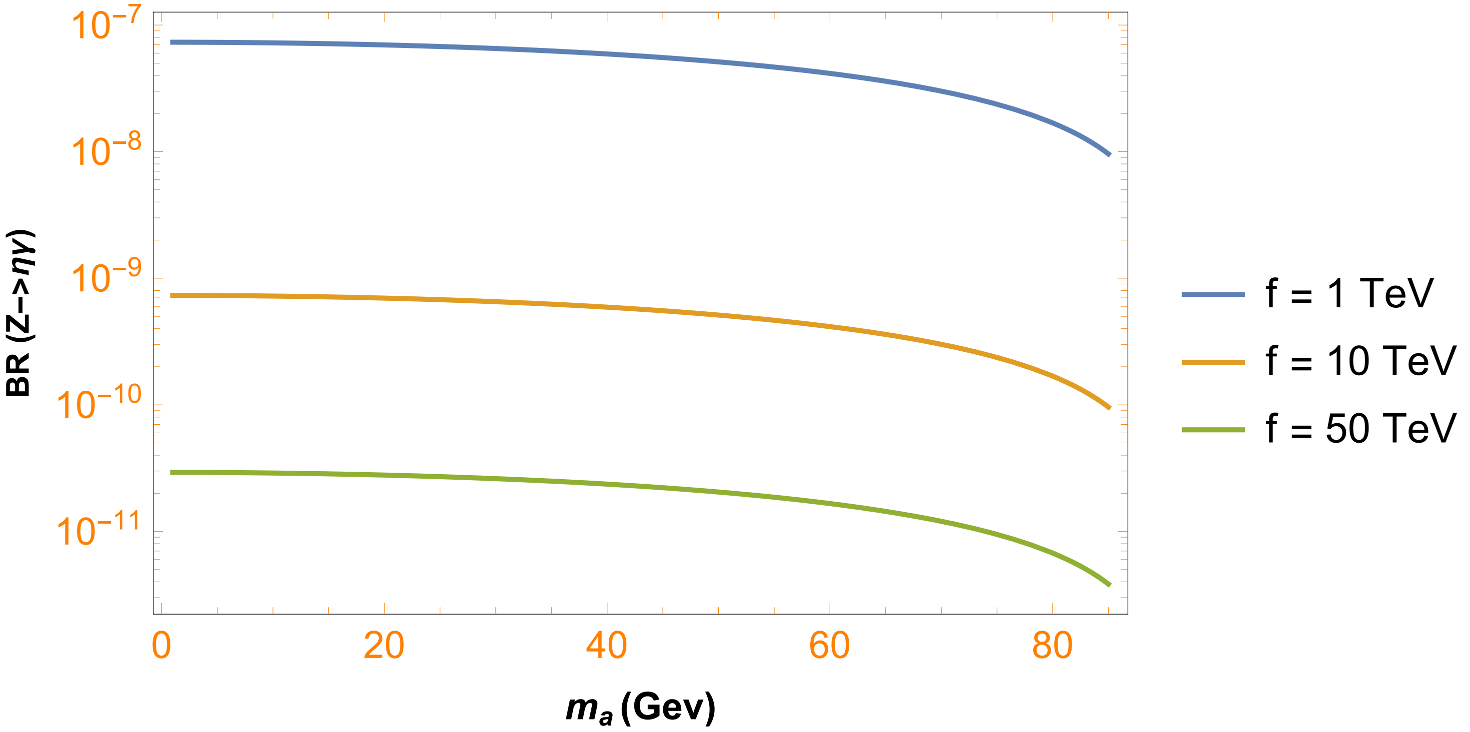


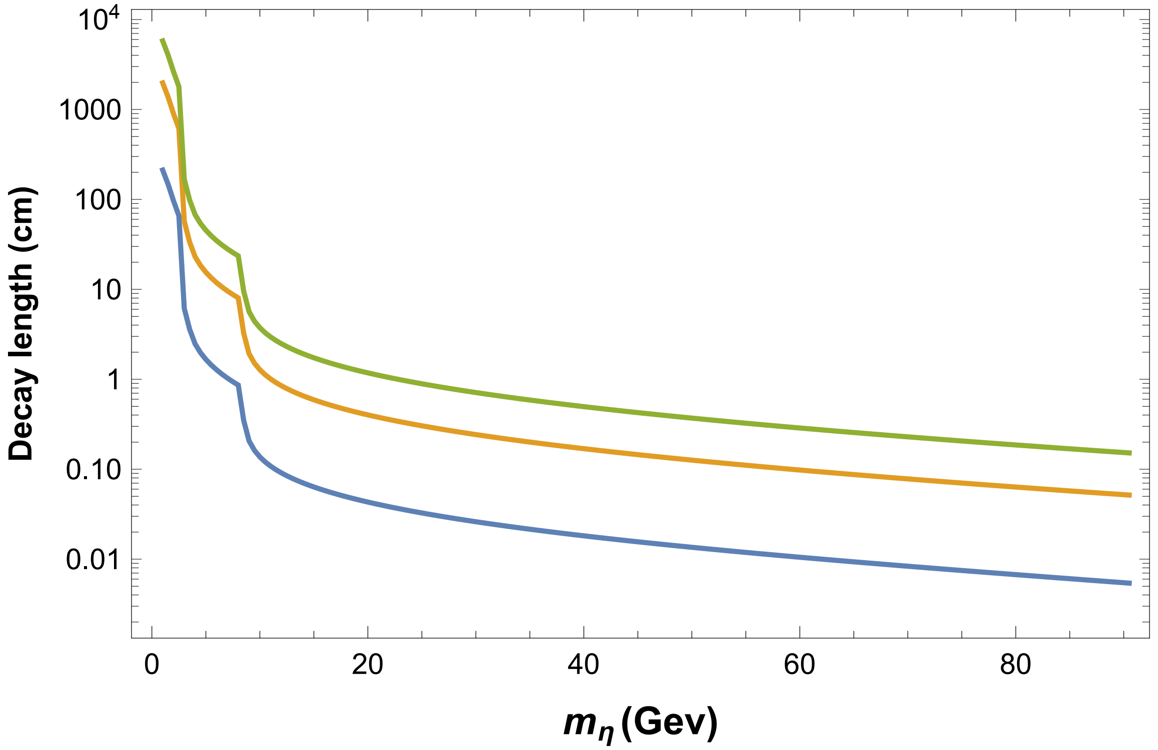
G.C., A.Deandrea, A.Iyer, Sridhar
2104.11064

This process is always associated with a monochromatic photon.

Tera Z phase of FCC-ee will lead to 5-6 10^12 Z bosons at the end of the run.

Ideal test for rare Z decays!!





Tera-Z portal to compositeness (via ALPs)

G.C., A.Deandrea, A.Iyer, Sridhar
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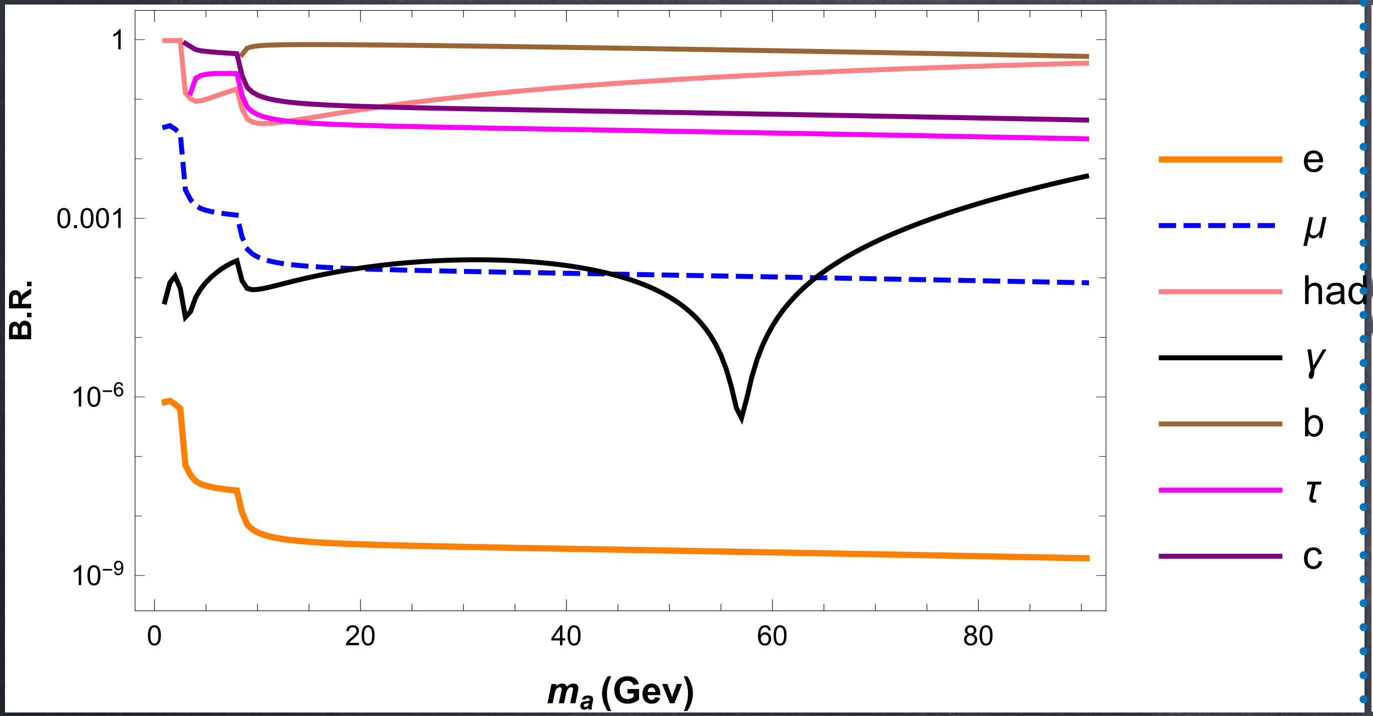
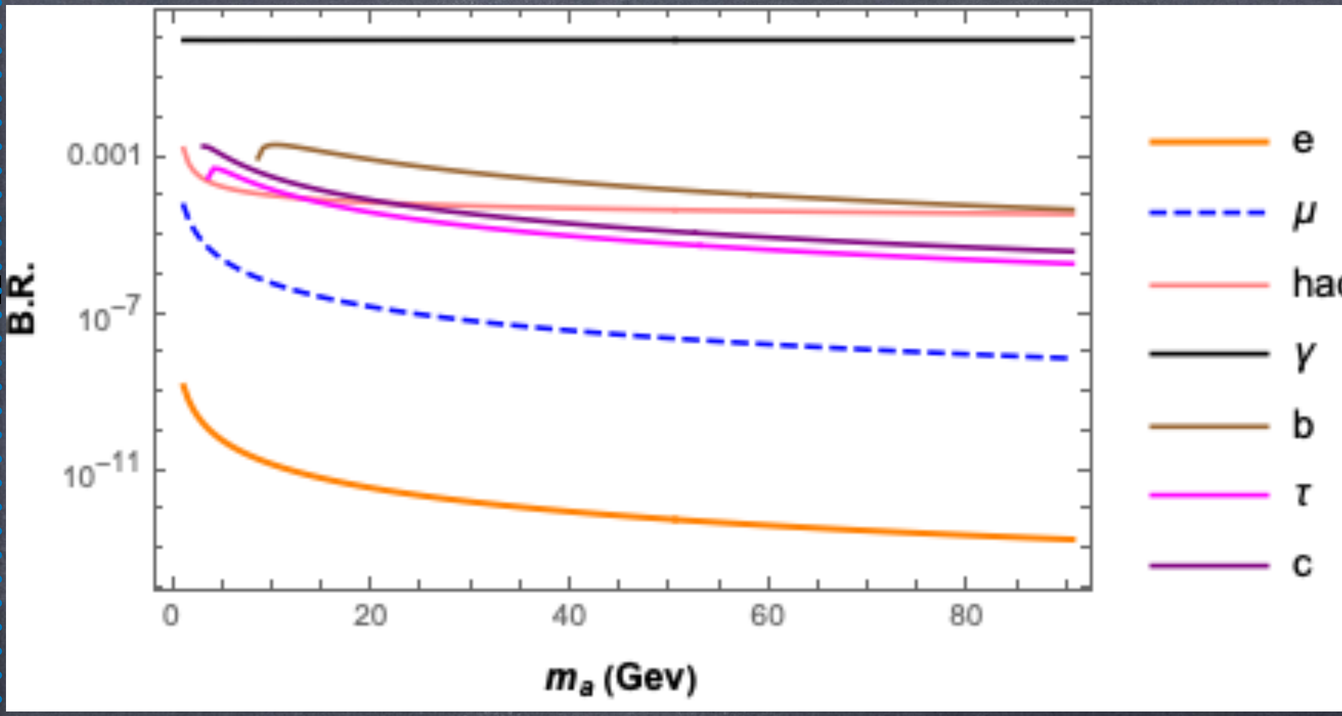
Photo-phobic

Photo-philic





No leading order coupling to Photons (WZW interaction is Zero!!)

eg. SU(4)/SP(4),
SU(4)xSU(4)/SU(4)

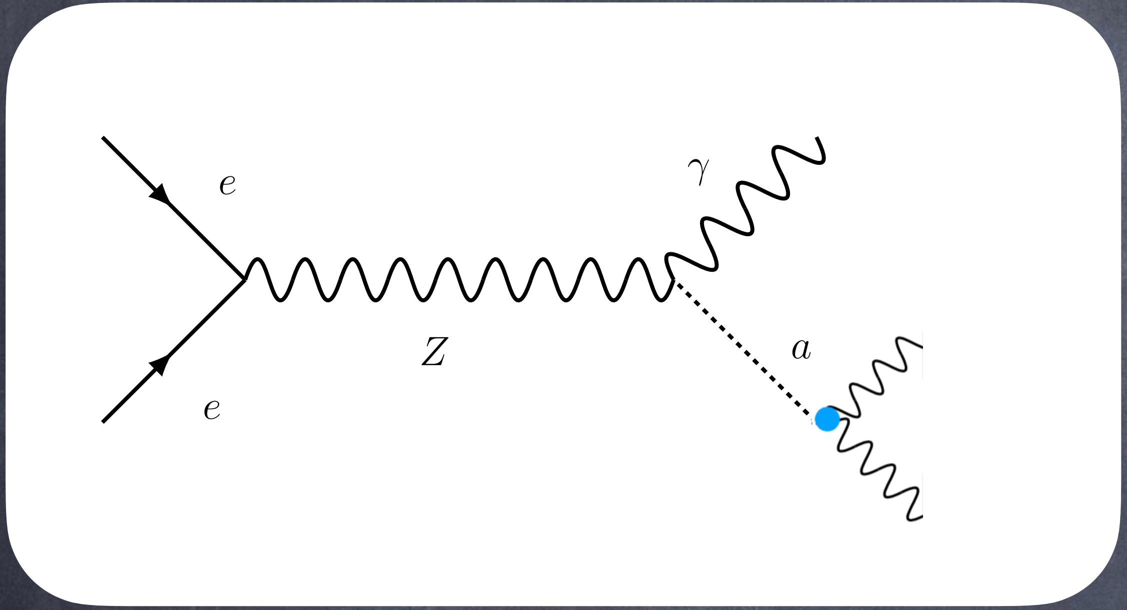
WZW interaction to photons (like the pion)

eg. SU(5)/SO(5),
SU(6)/SO(6)

Phenomenology-Prompt Decays

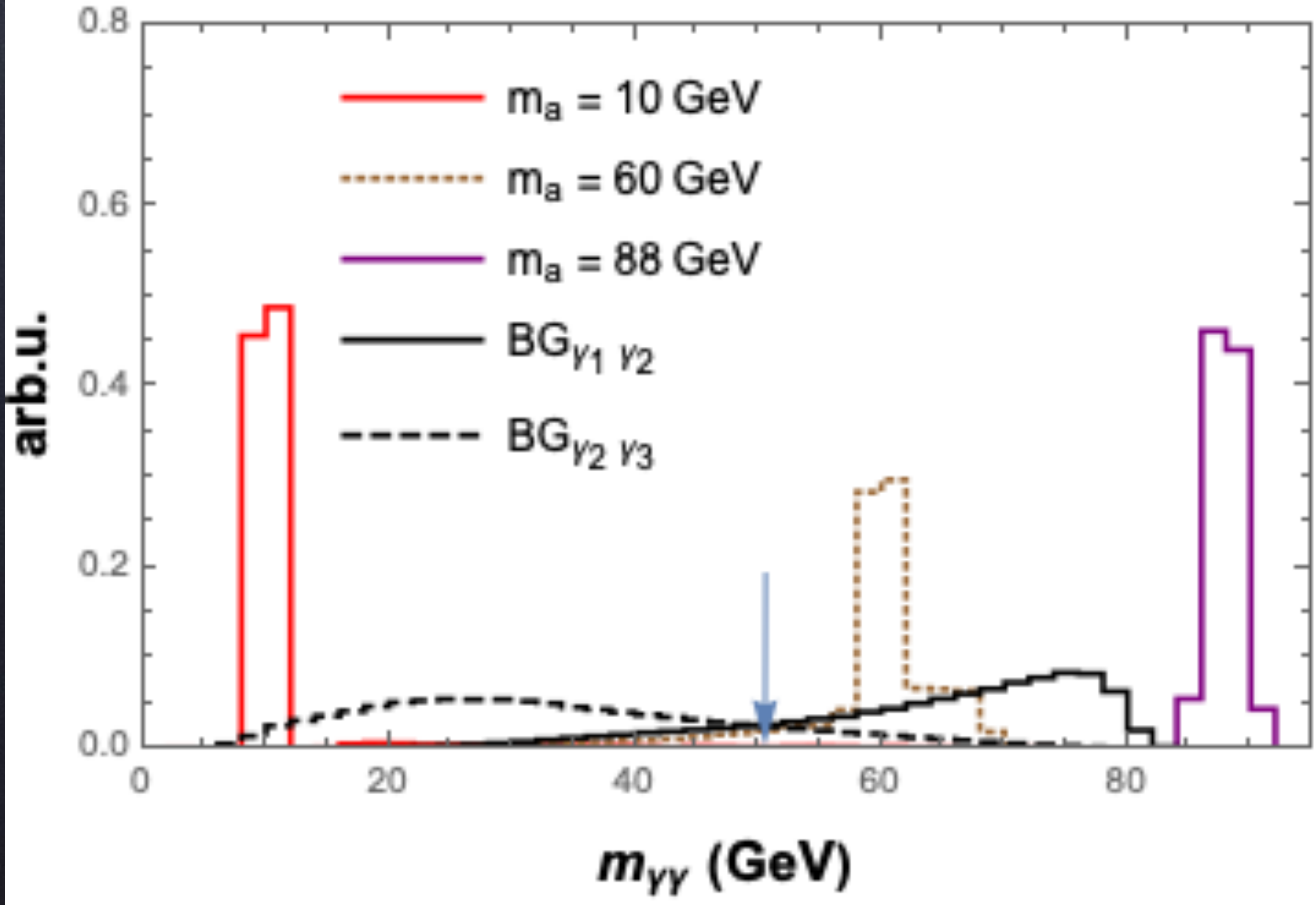
Photo-philic

G.C. et al.
2104.11064



- Three isolated photons

$$BR(Z \to 3\gamma)_{\text{LEP}} < 2.2 \cdot 10^{-6}$$



Discriminating variable:
invariant mass

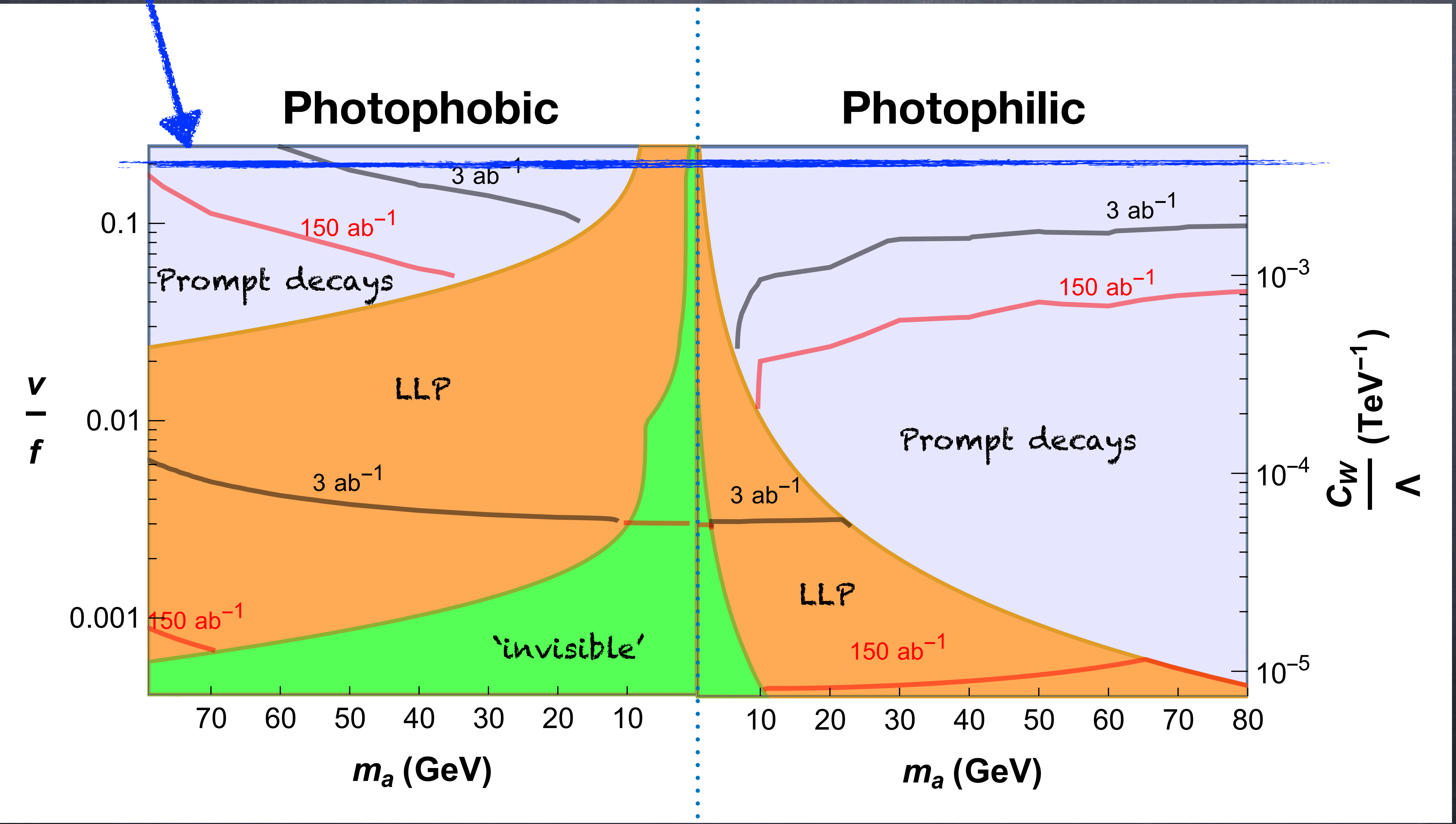
Photon ordering changes
at inv. mass 50 GeV

Bins above 80 GeV
populated by fakes:
hard to estimate!

Money plot

G.C., A.Deandrea, A.Iyer, Sridhar
2104.11064

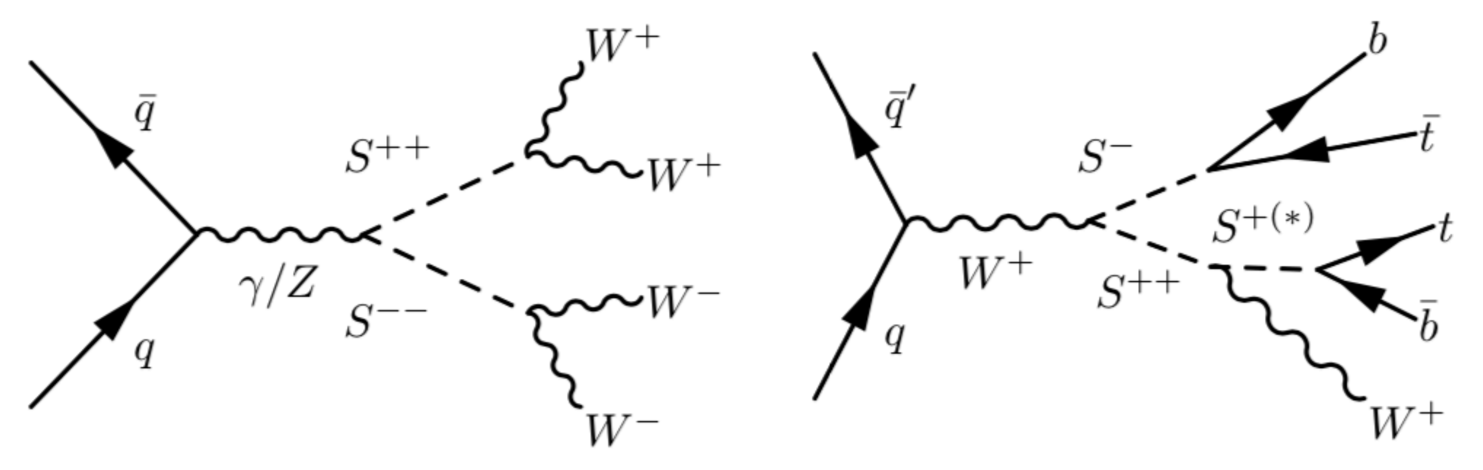
Typical EWPT bound



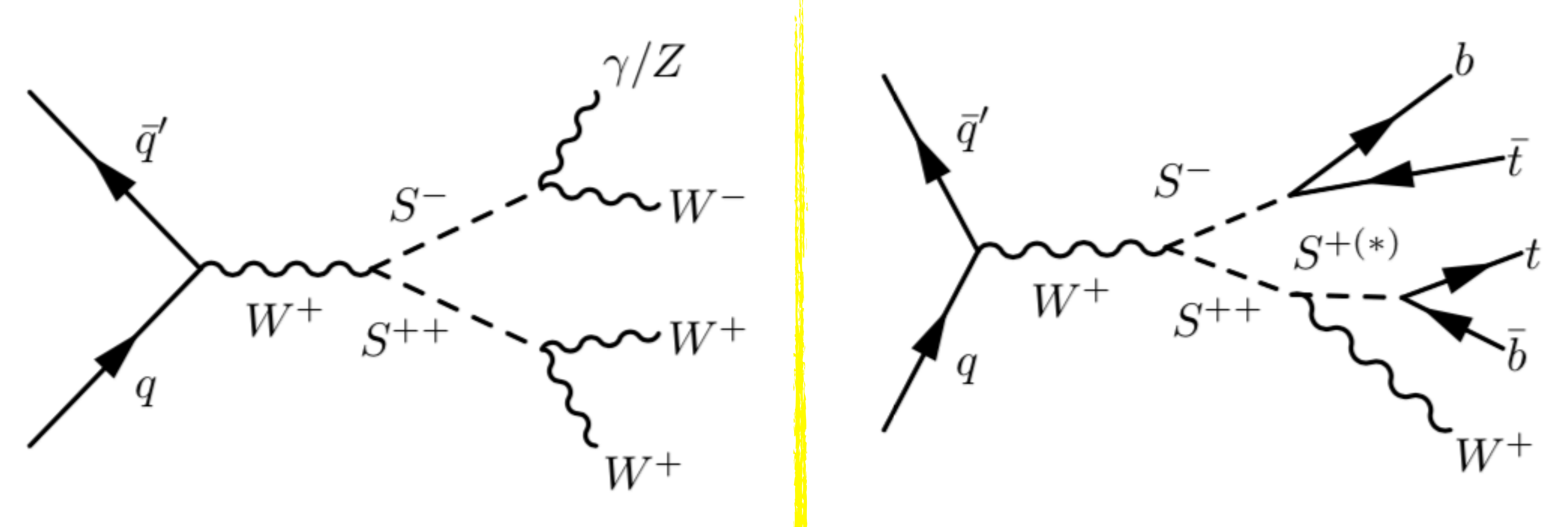
EW pNGB direct production

G.C., W.Porod, T.Flacke, L.Schwarze
2210.01826

- Dominantly pair-produced (no VEVs except for the doublet)
- Couplings to two EW gauge bosons via WZW
- Couplings to two fermions via partial compositeness
- Few dedicated direct searches (WWWW and WWWZ via doubly-charged scalar)



EW pNGB direct production

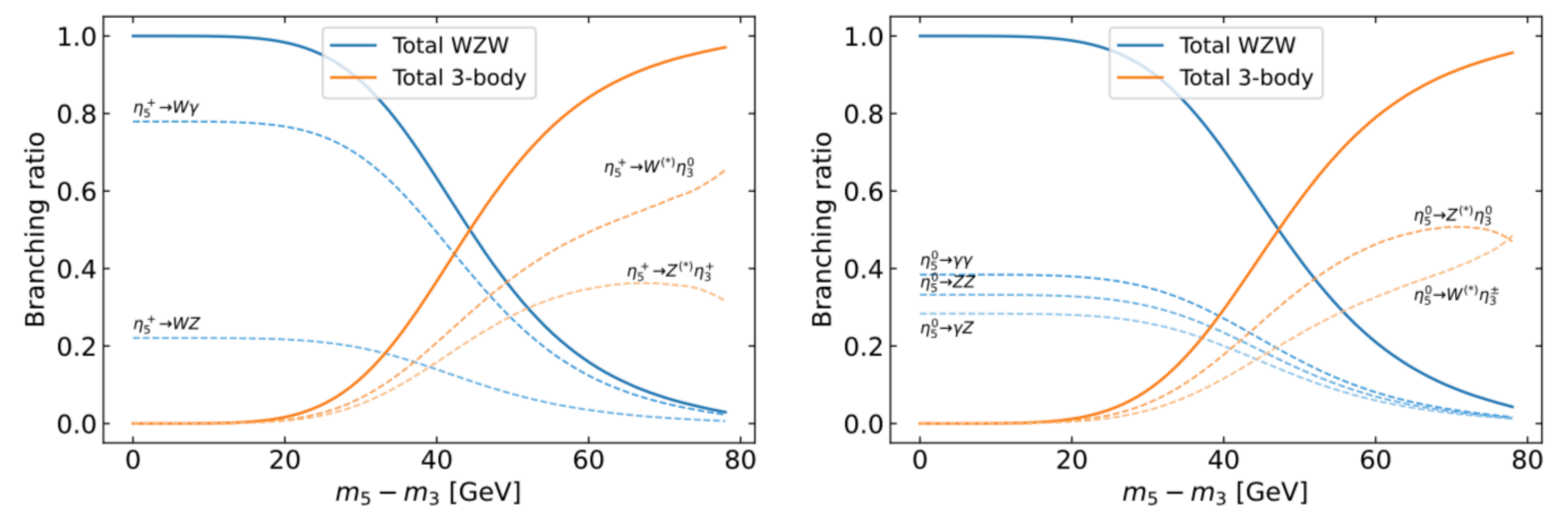


W.Porod et al.
2210.01826

- Decays to two GBs from WZW anomaly
- Small couplings
- Cascade decays can be competitive
- Photon-rich final states!

- Typically sizeable couplings to top and bottom
- Always dominate if present!
- They may be absent - model dependence!

Fermio-phobic SU(5)/SO(5) model



(c) Decays of η_5^+ for $m_5 = 600$ GeV $> m_3$

(d) Decays of η_5^0 for $m_5 = 600$ GeV $> m_3$

W.Porod et al.
2210.01826

- Decays to two GBs from WZW anomaly
- Small couplings
- Cascade decays can be competitive
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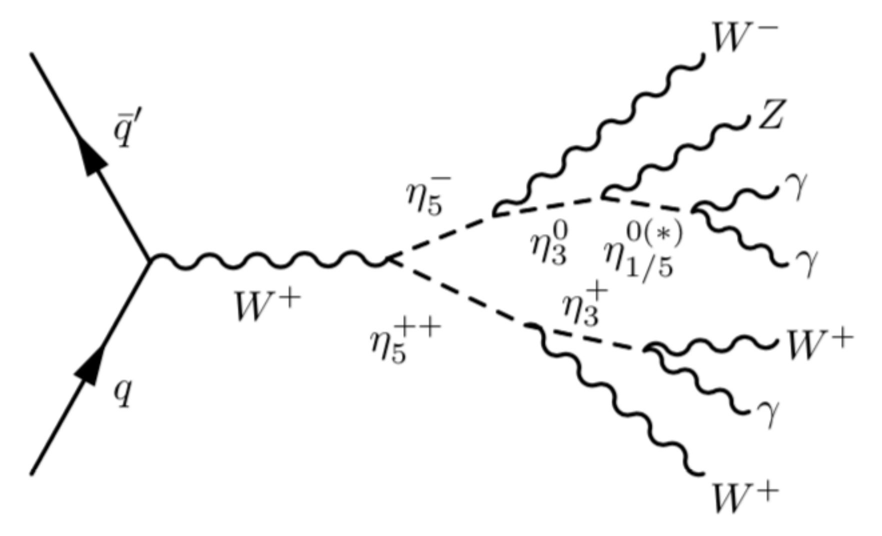
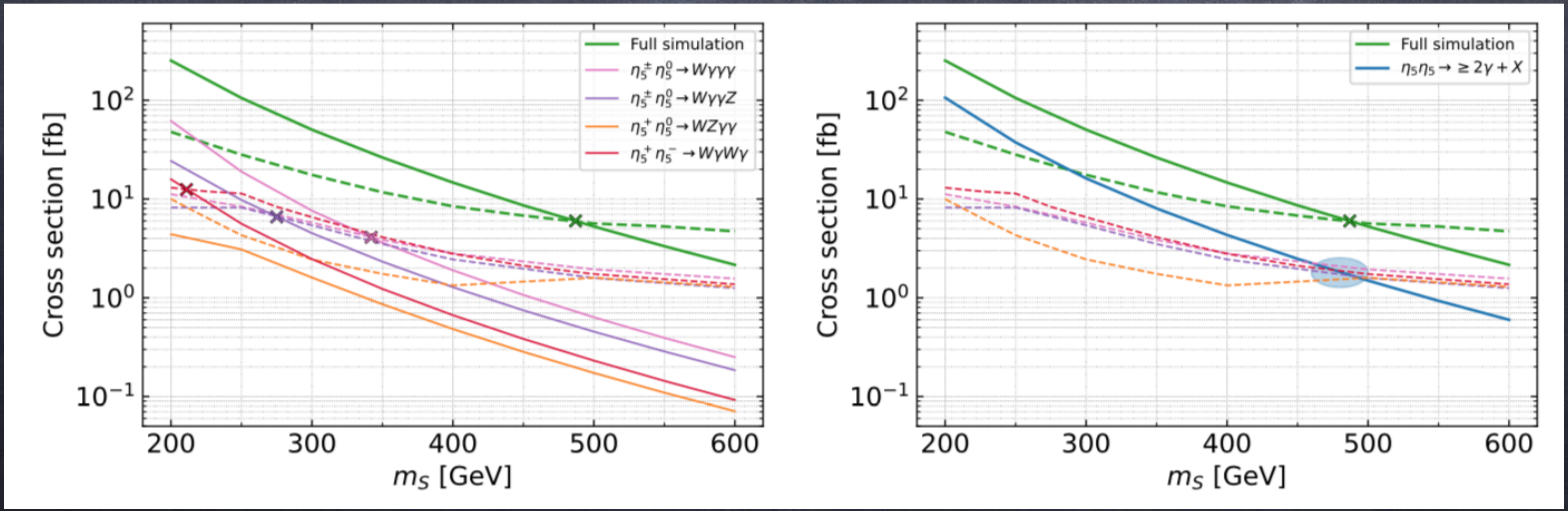
Cascade decays competitive for mass splits around 50 GeV



SU(5)/SO(5) benchmark

W.Porod et al.
2210.01826

- Run all searches in MadAnalysis, Checkmate and Contur on all di-scalar pair production channels.
- Best limits from multi-photon searches (ATLAS generic analysis)
- Many channels contribute to the same signal region!



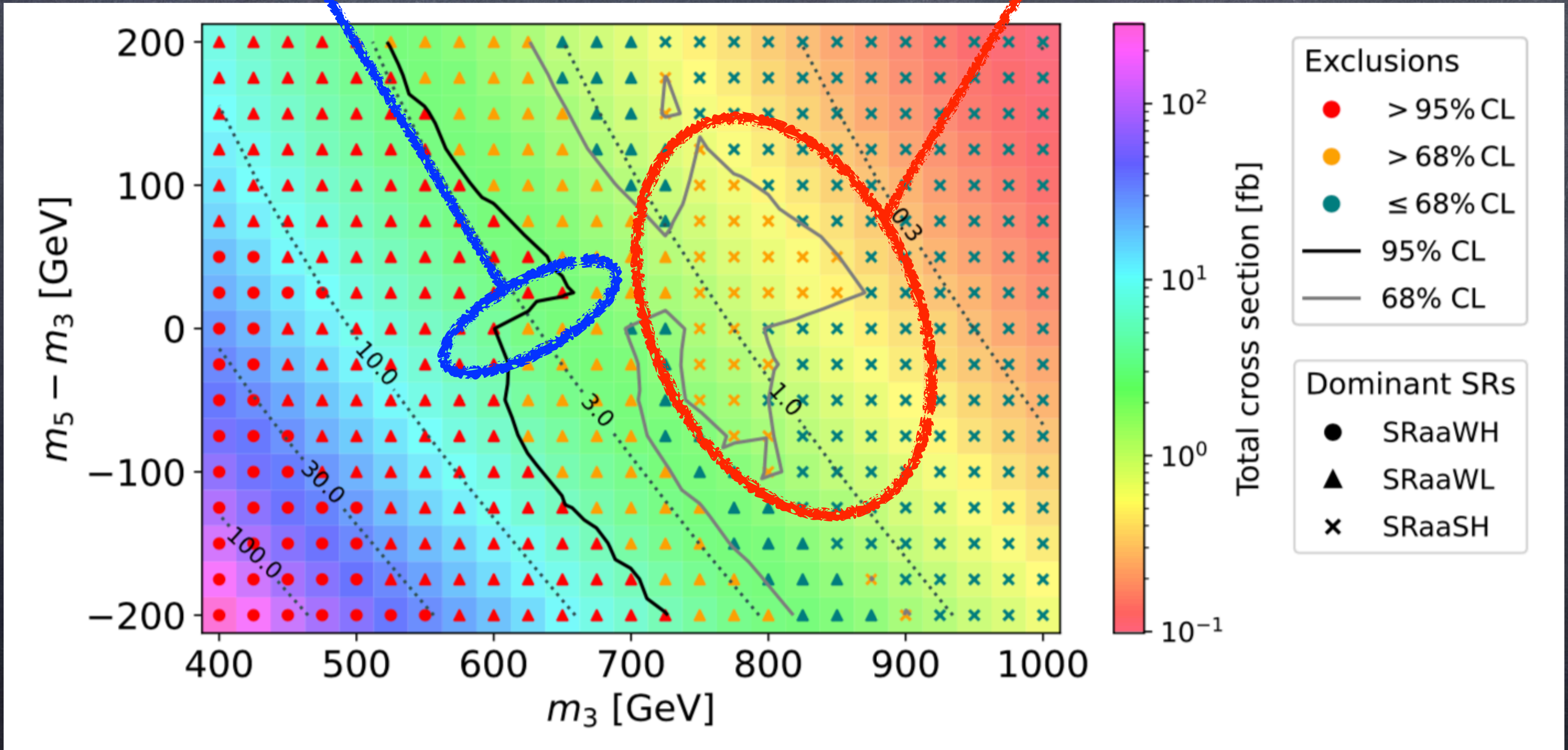
SU(5)/SO(5) benchmark

W.Porod et al.
2210.01826

Exclusion from multi-photon search

S++ cascade decays

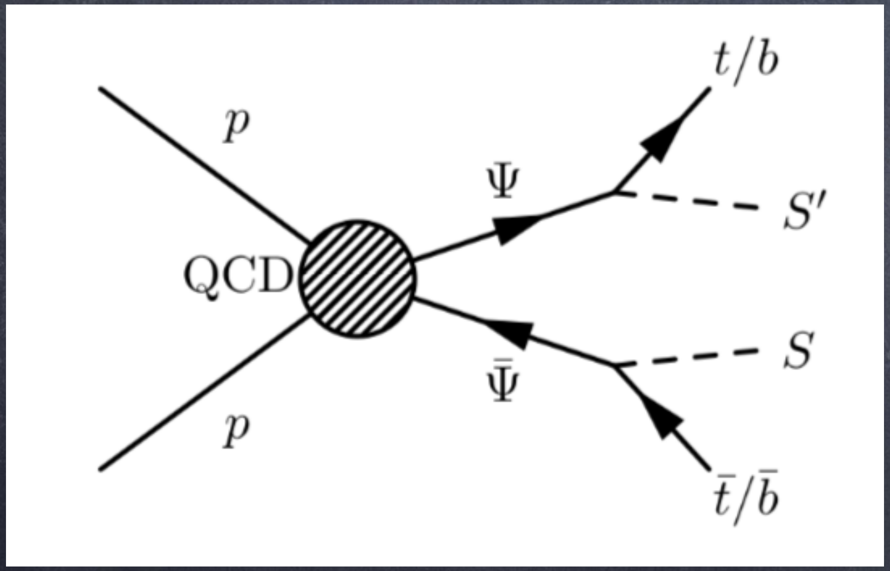
Change in dominant SR



Top partner pheno revisited

A.Banerjee et al
2203.0727 (Snowmass LOI)

- pNGBs lighter than the top partners are to be expected in all composite models



The S decays are model-dependent, but they can be classified:

$$\begin{aligned} S_i^{++} &\to W^+W^+ \\ S_i^{+} &\to W^+\gamma,\ W^+Z \\ S_i^{0} &\to W^+W^-,\ \gamma\gamma,\ \gamma Z,\ ZZ. \end{aligned}$$

Calculable ratios (from anomalies) and always present for all models.

$$\begin{aligned} S^{++} &\to W^+t\bar{b}, \\ S^{+} &\to t\bar{b}, \\ S^{0} &\to t\bar{t},\ b\bar{b}. \end{aligned}$$

Dominant, if present for the specific S.

Common exotic top partner decays

$$
\begin{aligned}
\mathcal{L}_{\Psi f V} = {} & \frac{e}{\sqrt{2} s_W} \kappa^W_{T,L} \overline{T} \not{W}^+ P_L b + \frac{e}{2 c_W s_W} \kappa^Z_{T,L} \overline{T} \not{Z} P_L t + \frac{e}{\sqrt{2} s_W} \kappa^W_{B,L} \overline{B} \not{W}^- P_L t \\
& + \frac{e}{2 c_W s_W} \kappa^Z_{B,L} \overline{B} \not{Z} P_L b + \frac{e}{\sqrt{2} s_W} \kappa^W_{X,L} \overline{X} \not{W}^+ P_L t + L \leftrightarrow R + \text{h.c.}
\end{aligned}
\tag{14}
$$

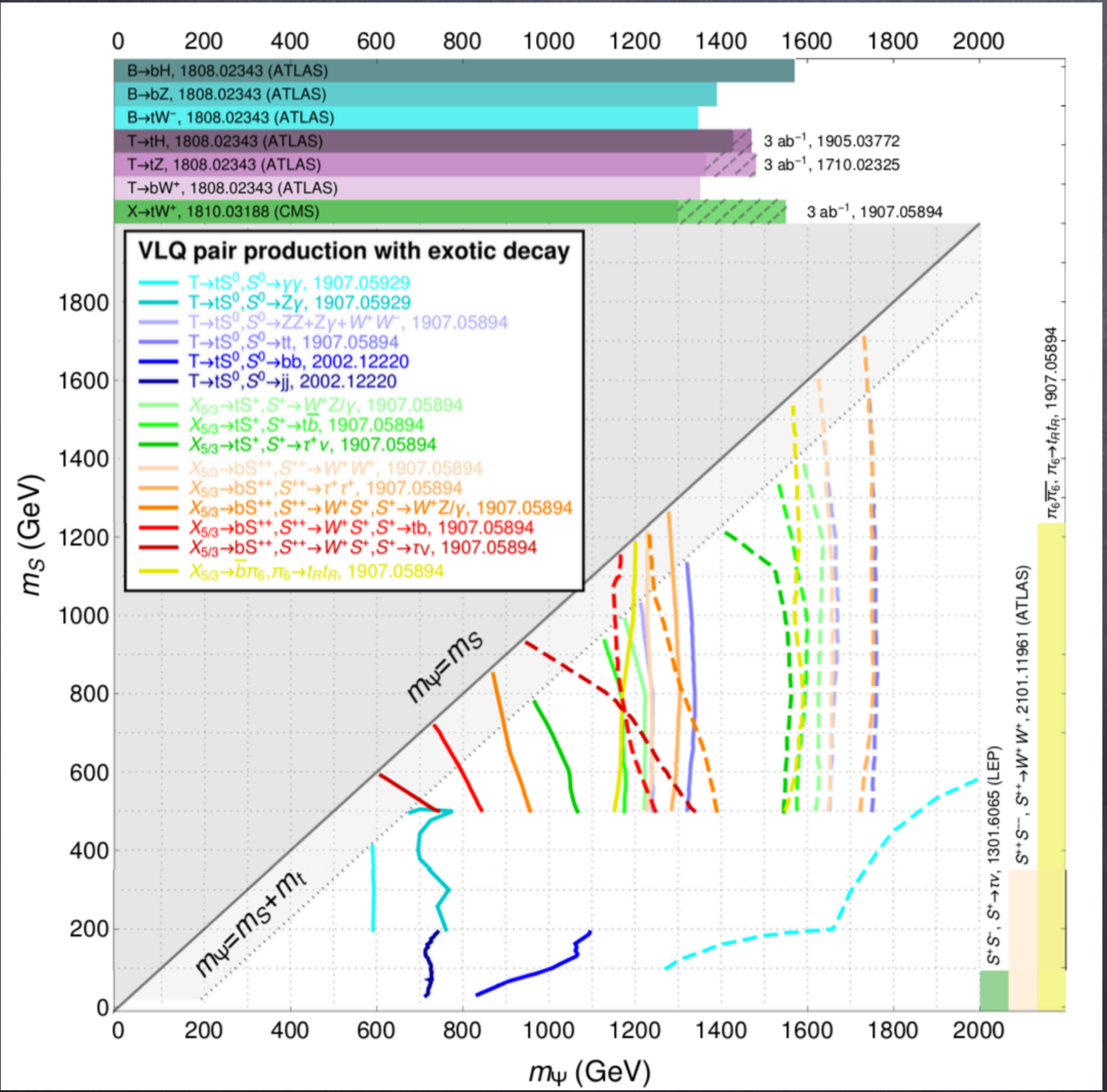
$$
\begin{aligned}
\mathcal{L}_{\Psi f S} = {} & \sum_i S_i^+ \left[\kappa^{S_i^+}_{T,L} \overline{T} P_L b + \kappa^{S_i^+}_{X,L} \overline{X} P_L t + L \leftrightarrow R \right] + \text{h.c.} + \sum_i S_i^- \left[\kappa^{S_i^-}_{B,L} \overline{B} P_L t + L \leftrightarrow R \right] + \text{h.c.} \\
& + \sum_i S_i^0 \left[\kappa^{S_i^0}_{T,L} \overline{T} P_L t + \kappa^{S_i^0}_{B,L} \overline{B} P_L b + L \leftrightarrow R \right] + \text{h.c.} \\
& + \sum_i S_i^{++} \left[\kappa^{S_i^{++}}_{X,L} \overline{X} P_L b + L \leftrightarrow R \right] + \text{h.c.}
\end{aligned}
\tag{15}
$$

- Possible to write a Master-Lagrangian containing all possible couplings, implemented at NLO in MG (FSMOG)

Work in progress (??)

Common exotic top partner decays

A.Banerjee et al
2203.0727 (Snowmass LOI)



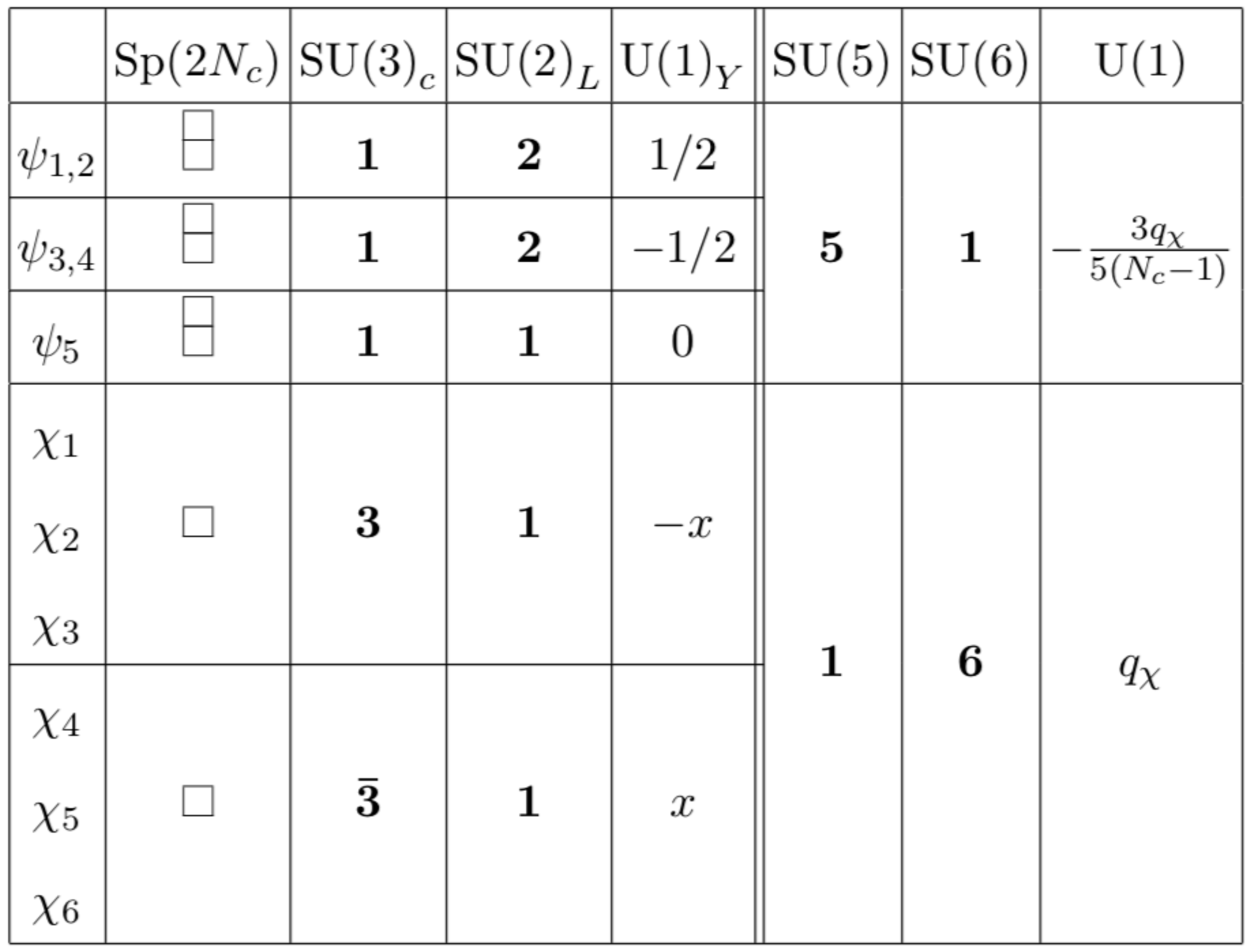
- Dedicated searches may be useful to push up the limits.
- Projections for FCC-hh are needed...
- in combination with scalar direct production.

Exotic top partners

G.C., T.Flacke, M.Kunkel, W.Porod
2112.00019

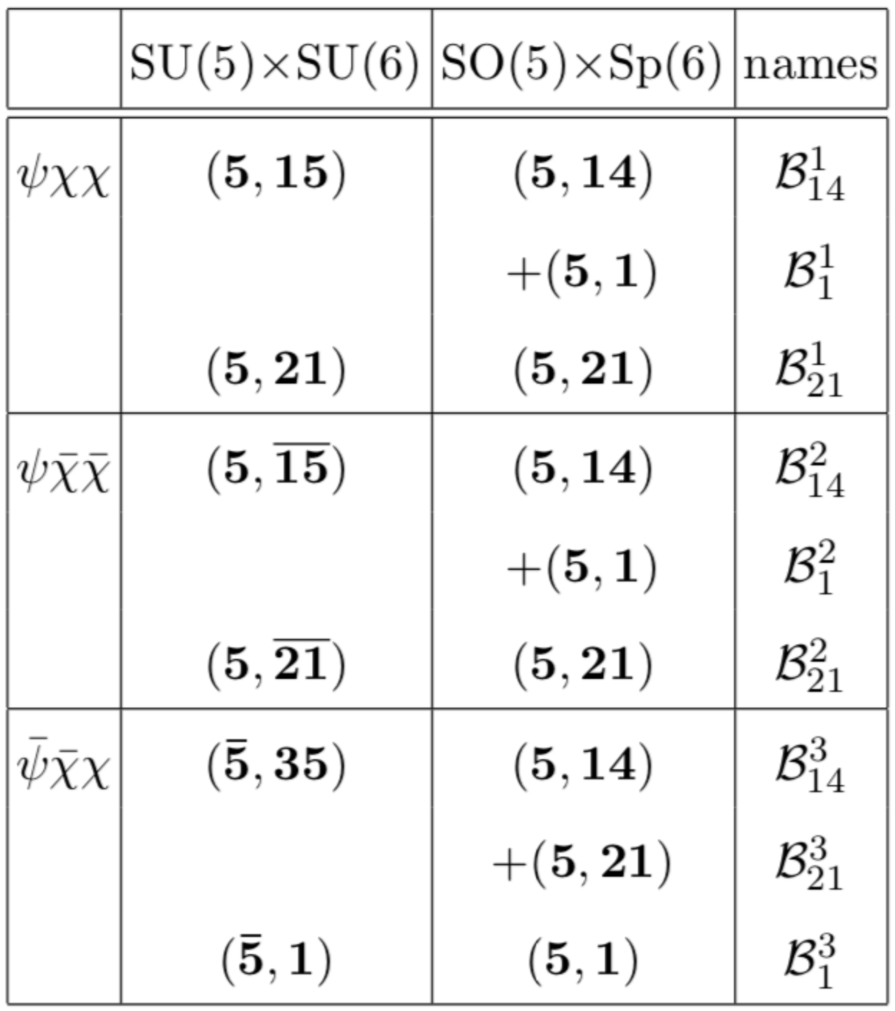
- A specific model: M5 of Ferretti's classification

Underlying fermions (like quarks)



	$Sp(2N_c)$	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$SU(5)$	$SU(6)$	$U(1)$
$\psi_{1,2}$	$\begin{smallmatrix}\Box\\\Box\end{smallmatrix}$	$\mathbf{1}$	$\mathbf{2}$	$1/2$	$\mathbf{5}$	$\mathbf{1}$	$-\frac{3q_\chi}{5(N_c-1)}$
$\psi_{3,4}$	$\begin{smallmatrix}\Box\\\Box\end{smallmatrix}$	$\mathbf{1}$	$\mathbf{2}$	$-1/2$			
ψ_5	$\begin{smallmatrix}\Box\\\Box\end{smallmatrix}$	$\mathbf{1}$	$\mathbf{1}$	0			
χ_1 χ_2 χ_3	$\Box$	$\mathbf{3}$	$\mathbf{1}$	$-x$	$\mathbf{1}$	$\mathbf{6}$	q_χ
χ_4 χ_5 χ_6	$\Box$	$\bar{\mathbf{3}}$	$\mathbf{1}$	x			

Baryons (top partners)



	$SU(5)\times SU(6)$	$SO(5)\times Sp(6)$	names
$\psi\chi\chi$	$(\mathbf{5},\mathbf{15})$	$(\mathbf{5},\mathbf{14})$	$\mathcal{B}^1_{14}$
		$+(\mathbf{5},\mathbf{1})$	$\mathcal{B}^1_{1}$
	$(\mathbf{5},\mathbf{21})$	$(\mathbf{5},\mathbf{21})$	$\mathcal{B}^1_{21}$
$\psi\bar{\chi}\bar{\chi}$	$(\mathbf{5},\overline{\mathbf{15}})$	$(\mathbf{5},\mathbf{14})$	$\mathcal{B}^2_{14}$
		$+(\mathbf{5},\mathbf{1})$	$\mathcal{B}^2_{1}$
	$(\mathbf{5},\overline{\mathbf{21}})$	$(\mathbf{5},\mathbf{21})$	$\mathcal{B}^2_{21}$
$\bar{\psi}\bar{\chi}\chi$	$(\bar{\mathbf{5}},\mathbf{35})$	$(\mathbf{5},\mathbf{14})$	$\mathcal{B}^3_{14}$
		$+(\mathbf{5},\mathbf{21})$	$\mathcal{B}^3_{21}$
	$(\bar{\mathbf{5}},\mathbf{1})$	$(\mathbf{5},\mathbf{1})$	$\mathcal{B}^3_{1}$

$$\mathbf{14} \to \mathbf{8_0} + \mathbf{3_{-2x}} + \bar{\mathbf{3}}_{\mathbf{2x}}\,,$$

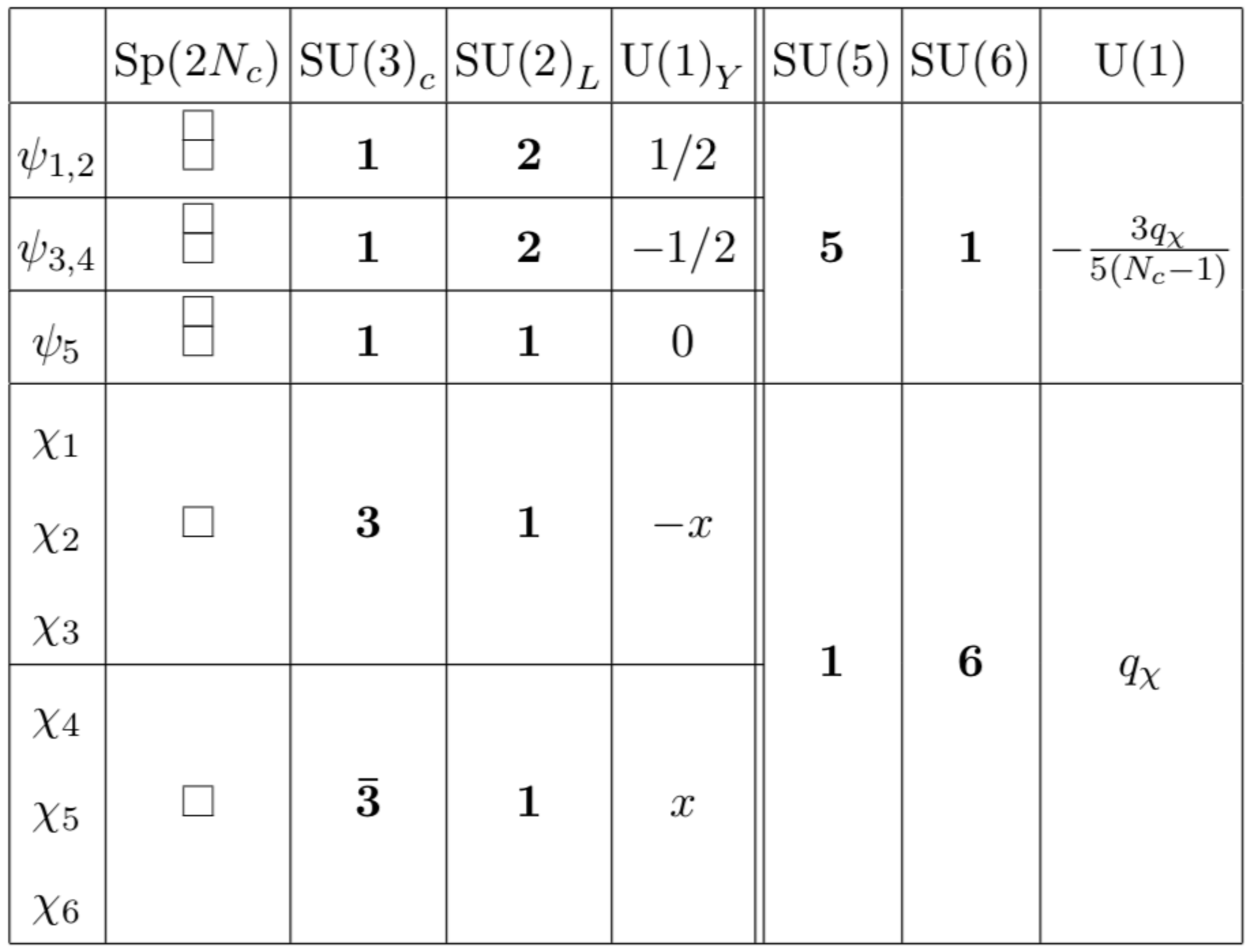
$$\mathbf{21} \to \mathbf{8_0} + \mathbf{6_{2x}} + \bar{\mathbf{6}}_{\mathbf{-2x}} + \mathbf{1_0}$$

Exotic top partners

G.C., T.Flacke, M.Kunkel, W.Porod
2112.00019

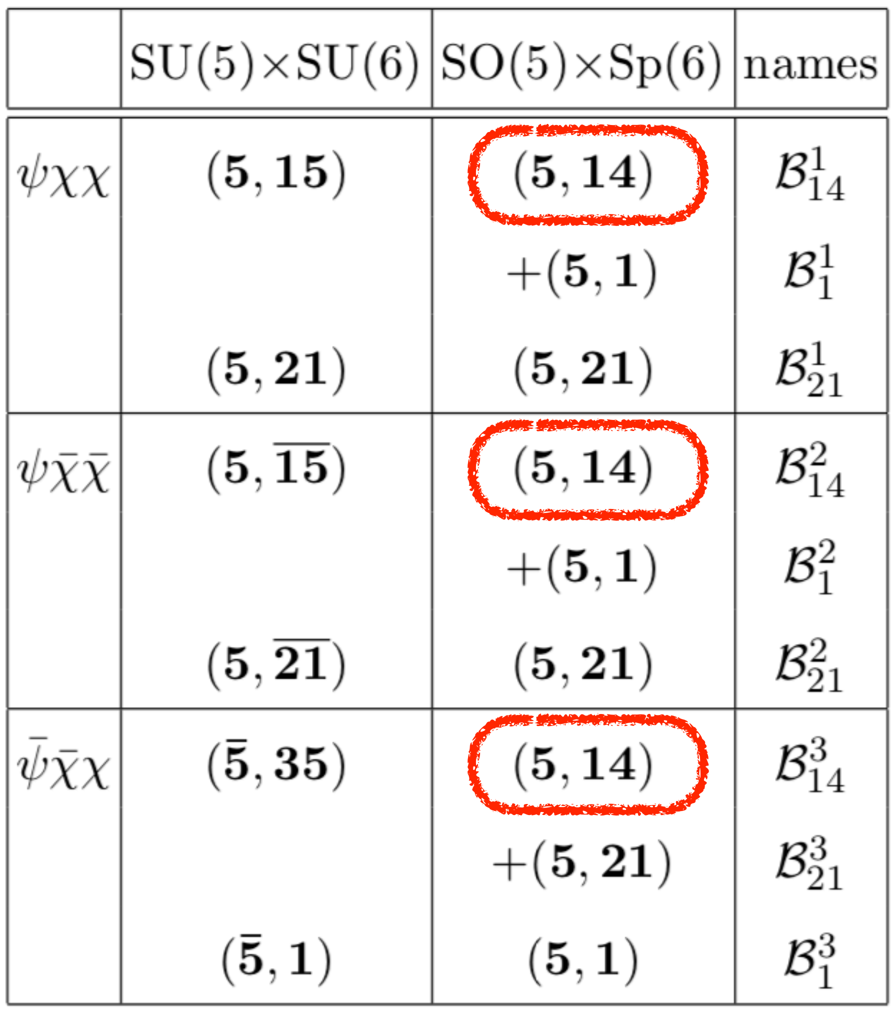
- A specific model: M5 of Ferretti's classification

Underlying fermions (like quarks)



	$Sp(2N_c)$	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$SU(5)$	$SU(6)$	$U(1)$
$\psi_{1,2}$	$\begin{smallmatrix}\square\\\square\end{smallmatrix}$	$\mathbf{1}$	$\mathbf{2}$	$1/2$	$\mathbf{5}$	$\mathbf{1}$	$-\frac{3q_\chi}{5(N_c-1)}$
$\psi_{3,4}$	$\begin{smallmatrix}\square\\\square\end{smallmatrix}$	$\mathbf{1}$	$\mathbf{2}$	$-1/2$			
ψ_5	$\begin{smallmatrix}\square\\\square\end{smallmatrix}$	$\mathbf{1}$	$\mathbf{1}$	0			
χ_1 χ_2 χ_3	$\square$	$\mathbf{3}$	$\mathbf{1}$	$-x$	$\mathbf{1}$	$\mathbf{6}$	q_χ
χ_4 χ_5 χ_6	$\square$	$\bar{\mathbf{3}}$	$\mathbf{1}$	x			

Baryons (top partners)



	$SU(5)\times SU(6)$	$SO(5)\times Sp(6)$	names
$\psi\chi\chi$	$(\mathbf{5},\mathbf{15})$	$(\mathbf{5},\mathbf{14})$	$\mathcal{B}^1_{14}$
		$+(\mathbf{5},\mathbf{1})$	$\mathcal{B}^1_{1}$
	$(\mathbf{5},\mathbf{21})$	$(\mathbf{5},\mathbf{21})$	$\mathcal{B}^1_{21}$
$\psi\bar\chi\bar\chi$	$(\mathbf{5},\overline{\mathbf{15}})$	$(\mathbf{5},\mathbf{14})$	$\mathcal{B}^2_{14}$
		$+(\mathbf{5},\mathbf{1})$	$\mathcal{B}^2_{1}$
	$(\mathbf{5},\overline{\mathbf{21}})$	$(\mathbf{5},\mathbf{21})$	$\mathcal{B}^2_{21}$
$\bar\psi\bar\chi\chi$	$(\bar{\mathbf{5}},\mathbf{35})$	$(\mathbf{5},\mathbf{14})$	$\mathcal{B}^3_{14}$
		$+(\mathbf{5},\mathbf{21})$	$\mathcal{B}^3_{21}$
	$(\bar{\mathbf{5}},\mathbf{1})$	$(\mathbf{5},\mathbf{1})$	$\mathcal{B}^3_{1}$

$$\mathbf{14} \to \mathbf{8}_0 + \mathbf{3}_{-2x} + \bar{\mathbf{3}}_{2x}$$

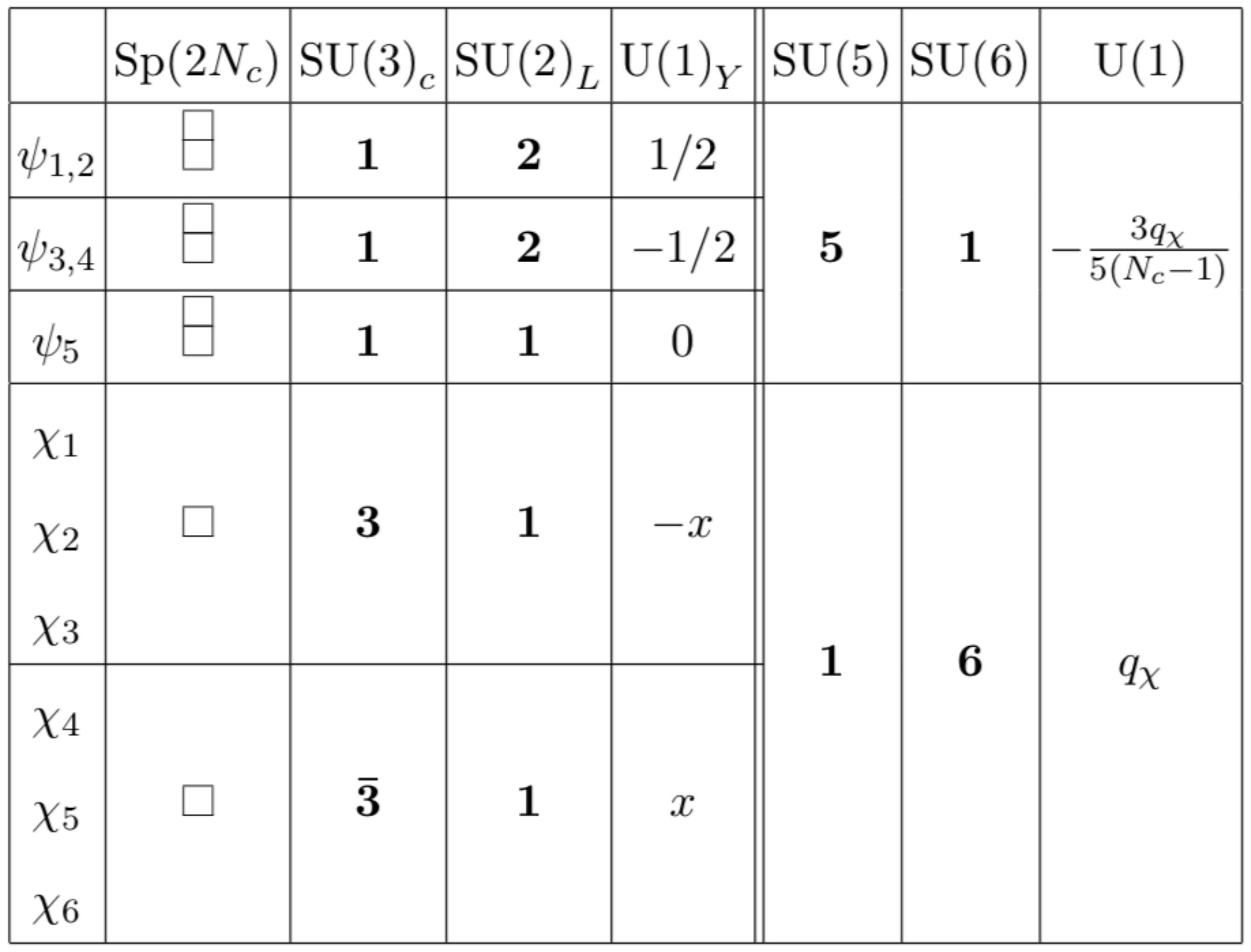
$$\mathbf{21} \to \mathbf{8}_0 + \mathbf{6}_{2x} + \bar{\mathbf{6}}_{-2x} + \mathbf{1}_0$$

Exotic top partners

G.C., T.Flacke, M.Kunkel, W.Porod
2112.00019

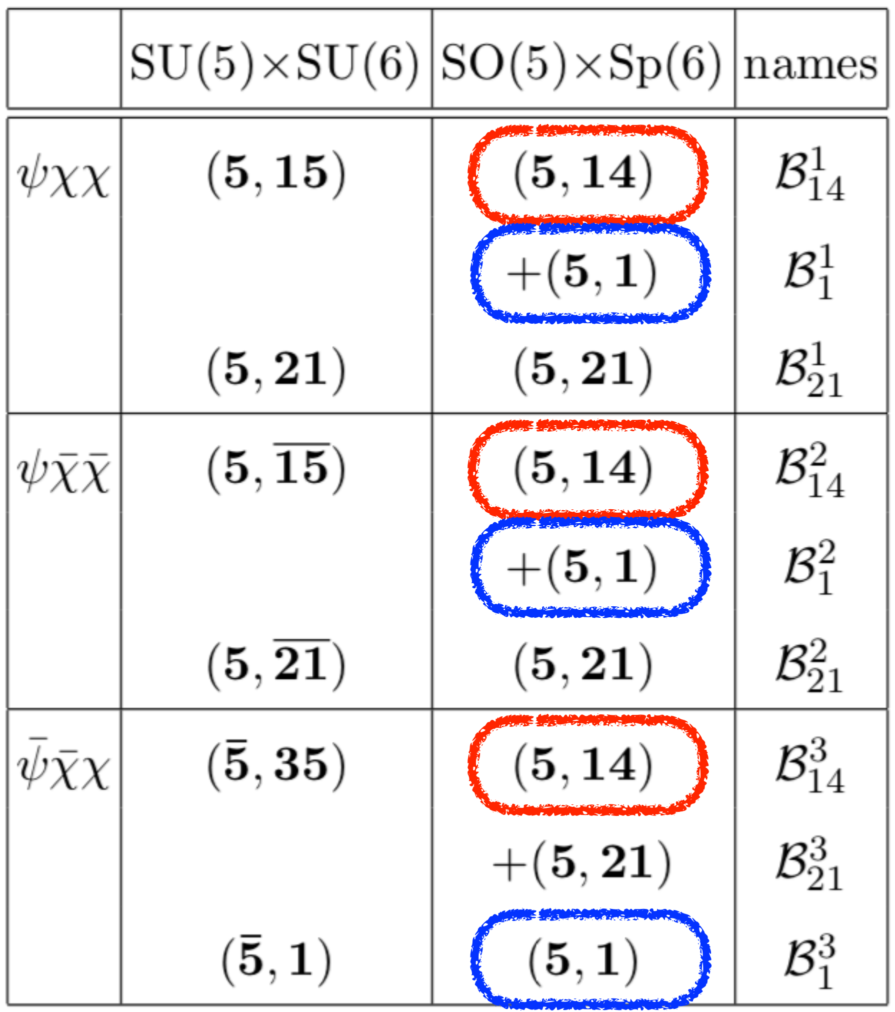
- A specific model: M5 of Ferretti's classification

Underlying fermions (like quarks)



	$Sp(2N_c)$	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$SU(5)$	$SU(6)$	$U(1)$
$\psi_{1,2}$	$\begin{array}{c}\square\\[-4pt]\square\end{array}$	$\mathbf{1}$	$\mathbf{2}$	$1/2$	$\mathbf{5}$	$\mathbf{1}$	$-\frac{3q_\chi}{5(N_c-1)}$
$\psi_{3,4}$	$\begin{array}{c}\square\\[-4pt]\square\end{array}$	$\mathbf{1}$	$\mathbf{2}$	$-1/2$			
ψ_5	$\begin{array}{c}\square\\[-4pt]\square\end{array}$	$\mathbf{1}$	$\mathbf{1}$	0			
χ_1 χ_2 χ_3	$\square$	$\mathbf{3}$	$\mathbf{1}$	$-x$	$\mathbf{1}$	$\mathbf{6}$	q_χ
χ_4 χ_5 χ_6	$\square$	$\bar{\mathbf{3}}$	$\mathbf{1}$	x			

Baryons (top partners)



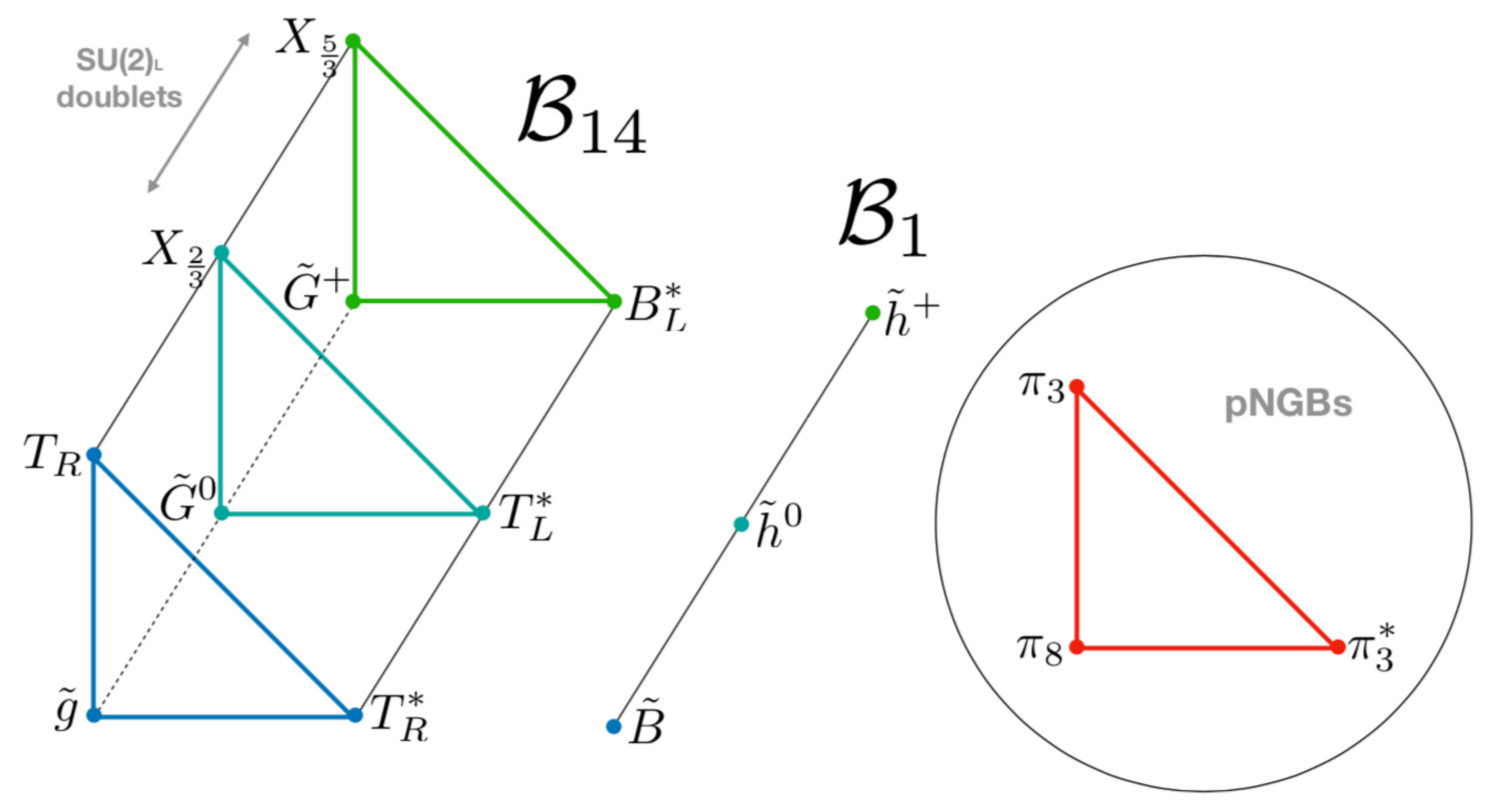
	$SU(5)\times SU(6)$	$SO(5)\times Sp(6)$	names
$\psi\chi\chi$	$(\mathbf{5},\mathbf{15})$	$(\mathbf{5},\mathbf{14})$ $+(\mathbf{5},\mathbf{1})$	$\mathcal{B}^1_{14}$ $\mathcal{B}^1_{1}$
	$(\mathbf{5},\mathbf{21})$	$(\mathbf{5},\mathbf{21})$	$\mathcal{B}^1_{21}$
$\psi\bar{\chi}\bar{\chi}$	$(\mathbf{5},\overline{\mathbf{15}})$	$(\mathbf{5},\mathbf{14})$ $+(\mathbf{5},\mathbf{1})$	$\mathcal{B}^2_{14}$ $\mathcal{B}^2_{1}$
	$(\mathbf{5},\overline{\mathbf{21}})$	$(\mathbf{5},\mathbf{21})$	$\mathcal{B}^2_{21}$
$\bar{\psi}\bar{\chi}\chi$	$(\bar{\mathbf{5}},\mathbf{35})$	$(\mathbf{5},\mathbf{14})$ $+(\mathbf{5},\mathbf{21})$	$\mathcal{B}^3_{14}$ $\mathcal{B}^3_{21}$
	$(\bar{\mathbf{5}},\mathbf{1})$	$(\mathbf{5},\mathbf{1})$	$\mathcal{B}^3_{1}$

$$\mathbf{14} \to \mathbf{8}_0 + \mathbf{3}_{-2x} + \bar{\mathbf{3}}_{2x}$$

$$\mathbf{21} \to \mathbf{8}_0 + \mathbf{6}_{2x} + \bar{\mathbf{6}}_{-2x} + \mathbf{1}_0$$

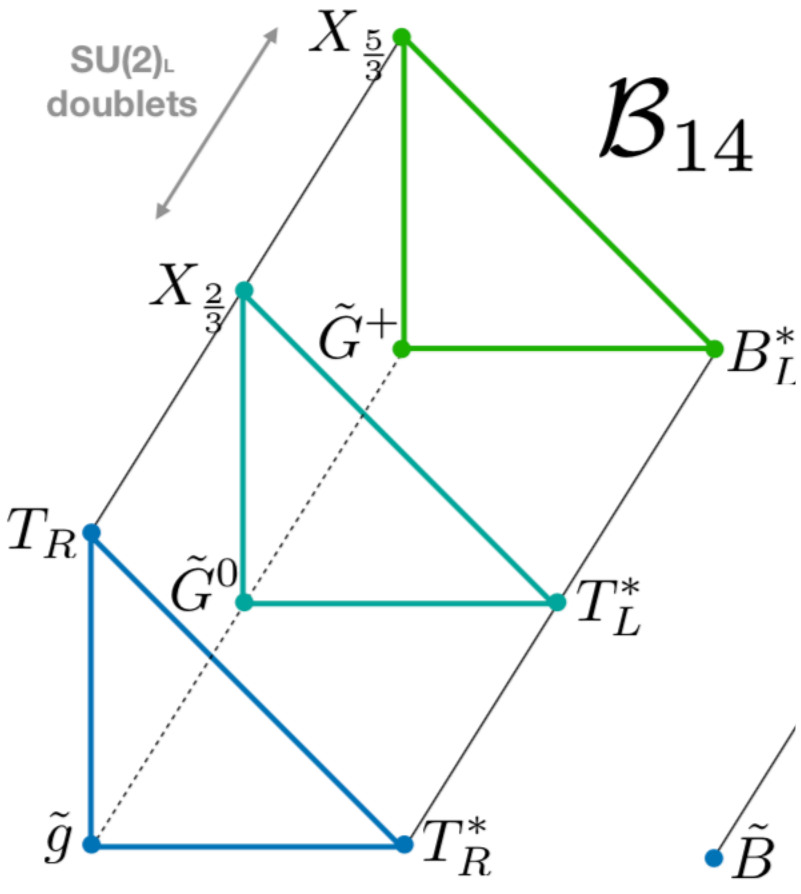
Exotic top partners

G.C., T.Flacke, M.Kunkel, W.Porod
2112.00019



Exotic top partners

G.C., T.Flacke, M.Kunkel, W.Porod
2112.00019



Octoni (Dirac): $\tilde{G}^+ = \begin{pmatrix} \tilde{G}_u^+ \\ \bar{\tilde{G}}_d^- \end{pmatrix}$, $\tilde{G}^0 = \begin{pmatrix} \tilde{G}_u^0 \\ \bar{\tilde{G}}_d^0 \end{pmatrix}$,

Gluoni (Majorana): $\tilde{g} = \begin{pmatrix} \tilde{g} \\ \bar{\tilde{g}} \end{pmatrix}$;

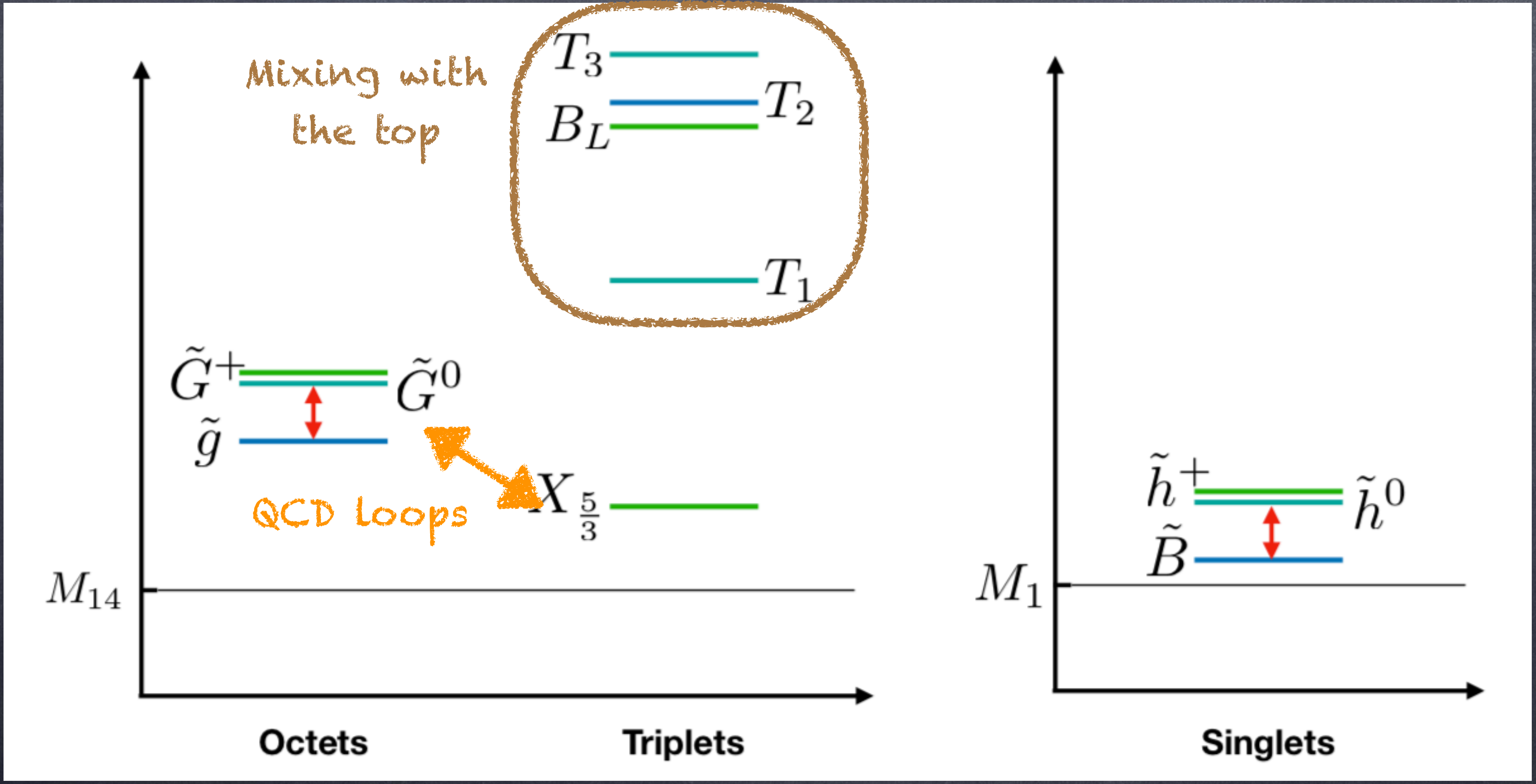
Higgsoni (Dirac): $\tilde{h}^+ = \begin{pmatrix} \tilde{h}_u^+ \\ \bar{\tilde{h}}_d^- \end{pmatrix}$, $\tilde{h}^0 = \begin{pmatrix} \tilde{h}_u^0 \\ \bar{\tilde{h}}_d^0 \end{pmatrix}$,

Boni (Majorana): $\tilde{B} = \begin{pmatrix} \tilde{B} \\ \bar{\tilde{B}} \end{pmatrix}$.

The baryon content looks ironically SUSY-like!

Exotic top partners

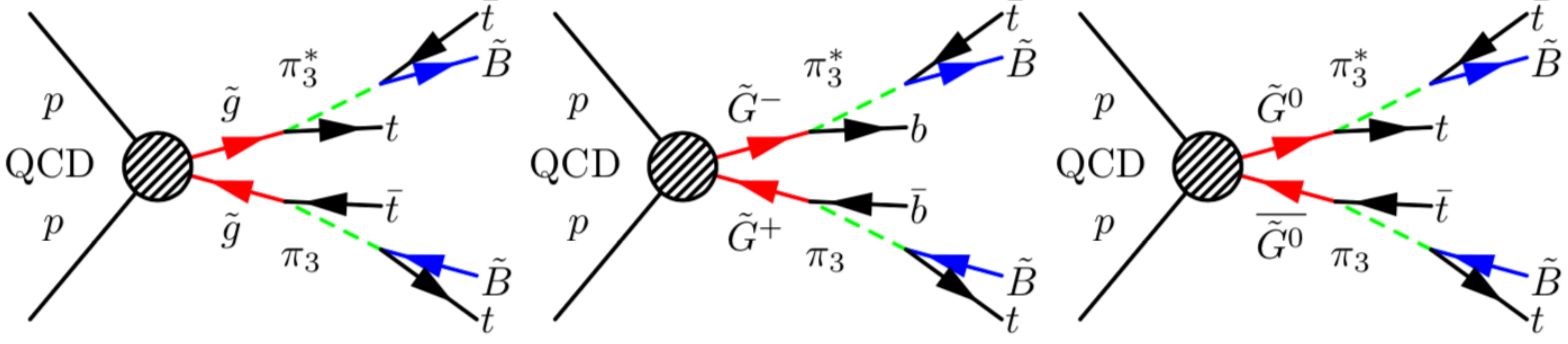
G.Cacciapaglia et al.
2112.00019



Octoni bounds

G.C., T.Flacke, M.Kunkel, W.Porod
2112.00019

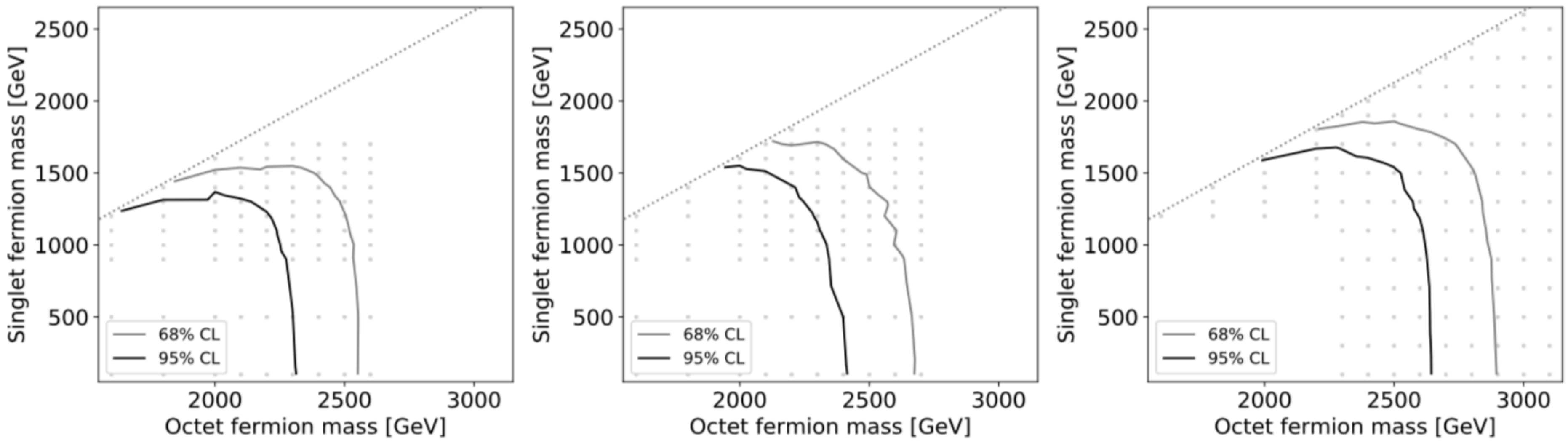
- Model implemented in MG.
- Check limits from searches in MadAnalysis and CheckMate.
- Strongest bound from gluino and stop searches!



(a) $\tilde{g} \to \bar{t}\pi_3, t\pi_3^* \to \bar{t}t\tilde{B}$

(b) $\tilde{G}^+ \to \bar{b}\pi_3 \to \bar{b}t\tilde{B}$

(c) $\tilde{G}^0 \to \bar{t}\pi_3 \to \bar{t}t\tilde{B}$



(a) $\tilde{g} \to \bar{t}\pi_3, t\pi_3^* \to \bar{t}t\tilde{B}$,

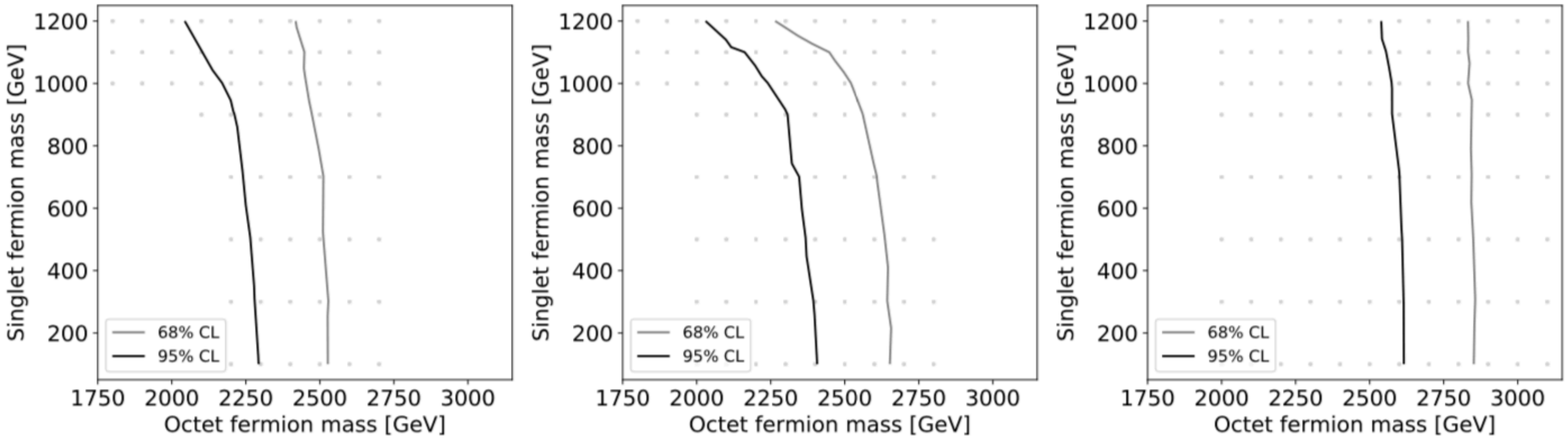
$m_{\tilde{g}} - m_{\pi_3} = 200$ GeV

(b) $\tilde{G}^+ \to \bar{b}\pi_3 \to \bar{b}t\tilde{B}$,

$m_{\tilde{G}^+} - m_{\pi_3} = 200$ GeV

(c) $Q_8 \to \bar{q}\pi_3 \to \bar{q}t\tilde{B}$,

$m_{Q_8} - m_{\pi_3} = 200$ GeV



(d) $\tilde{g} \to \bar{t}\pi_3, t\pi_3^* \to \bar{t}t\tilde{B}$,

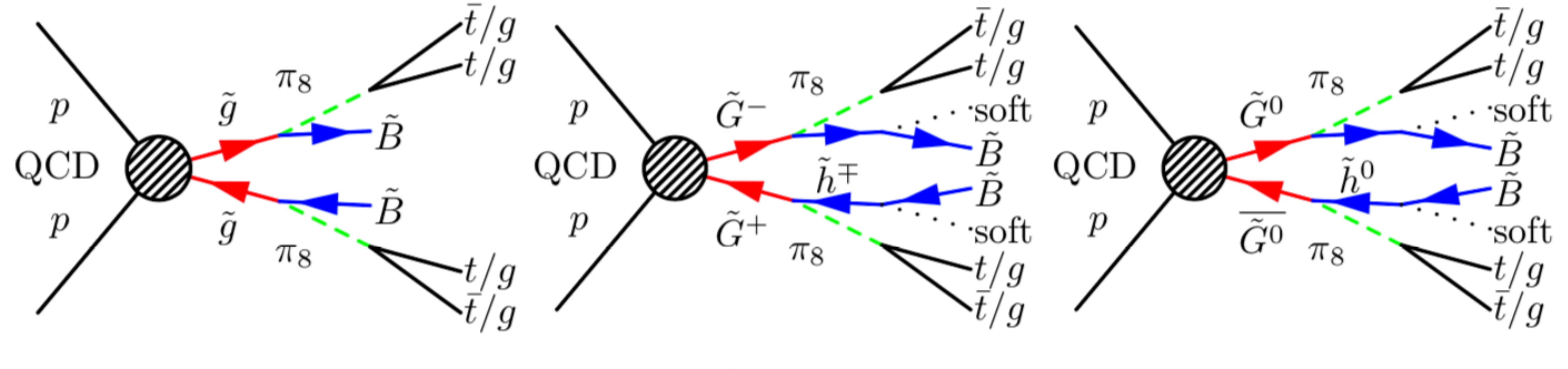
$m_{\pi_3} = 1.4$ TeV

(e) $\tilde{G}^+ \to \bar{b}\pi_3 \to \bar{b}t\tilde{B}$,

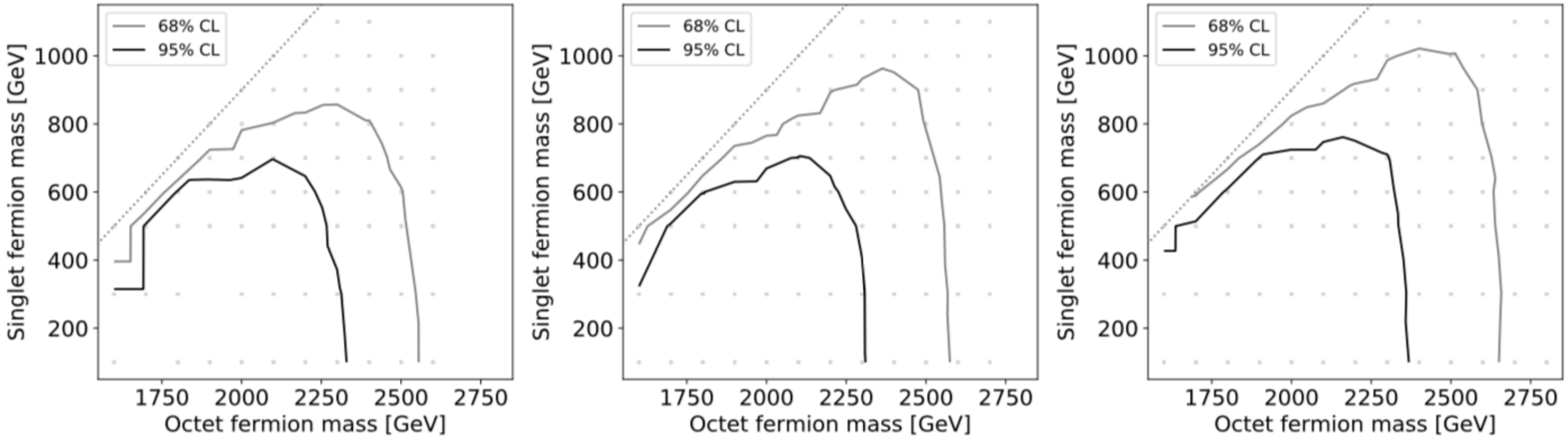
$m_{\pi_3} = 1.4$ TeV

(f) $Q_8 \to \bar{q}\pi_3 \to \bar{q}t\tilde{B}$,

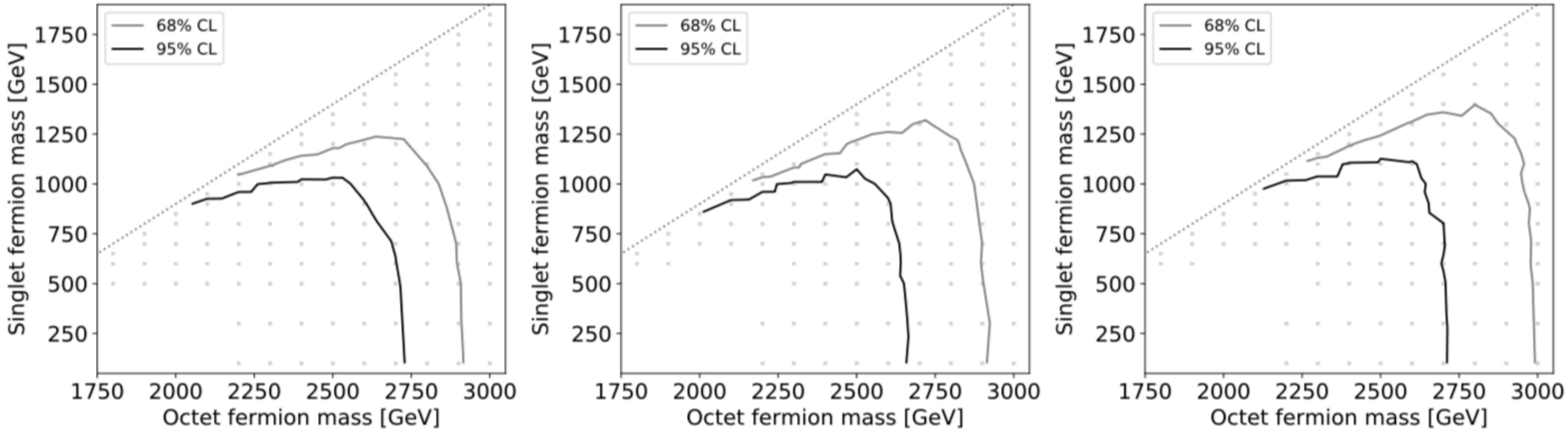
$m_{\pi_3} = 1.4$ TeV



(a) $\tilde{g} \to \tilde{B}\pi_8,\ \pi_8 \to \bar{t}t/gg.$ (b) $\tilde{G}^+ \to \tilde{h}^+\pi_8,\ \pi_8 \to \bar{t}t/gg.$ (c) $\tilde{G}^0 \to \tilde{h}^0\pi_8,\ \pi_8 \to \bar{t}t/gg.$



(a) $\tilde{g} \to \pi_8\tilde{B},\ \pi_8 \to gg$ (b) $\tilde{g} \to \pi_8\tilde{B},\ \pi_8 \to gg, t\bar{t}$ (c) $\tilde{g} \to \pi_8\tilde{B},\ \pi_8 \to t\bar{t}$



(d) $Q_8 \to \pi_8 Q_1,\ \pi_8 \to gg$ (e) $Q_8 \to \pi_8 Q_1,\ \pi_8 \to gg, t\bar{t}$ (f) $Q_8 \to \pi_8 Q_1,\ \pi_8 \to t\bar{t}$

Coloured pNGBs

- They are always present in models.
- They are relatively light (TeV scale)

$$\text{Octet}\begin{cases}\pi_8 \to t\bar{t} \\ \pi_8 \to gg\,,g\gamma\end{cases}$$

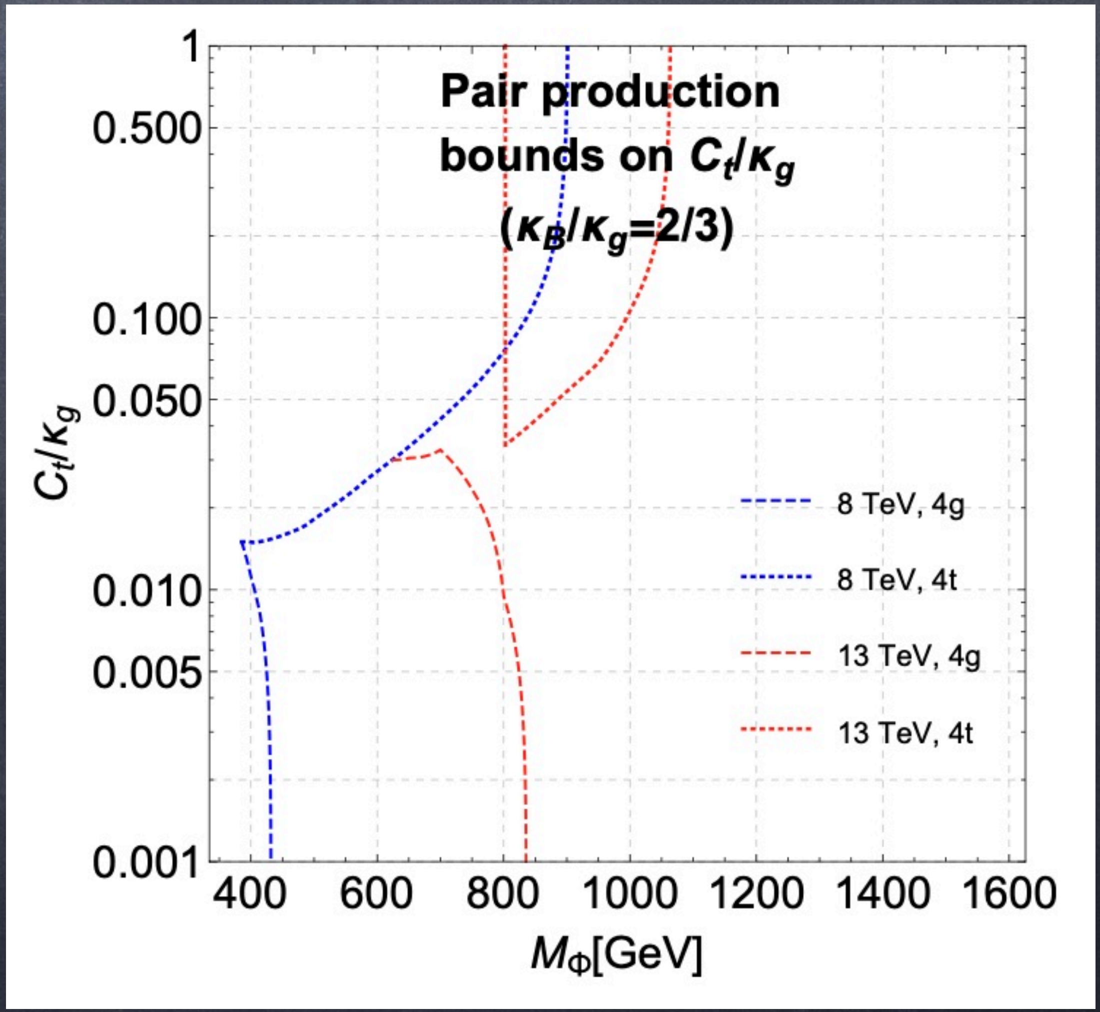
(sqluon-like)

$$\text{Triplet}\begin{cases}\pi_3 \to b\bar{s} \\ \pi_3 \to t\chi\end{cases}$$

(stop-like)

$$\text{Sextet}\begin{cases}\pi_6 \to tt \\ \pi_6 \to bb\end{cases}$$

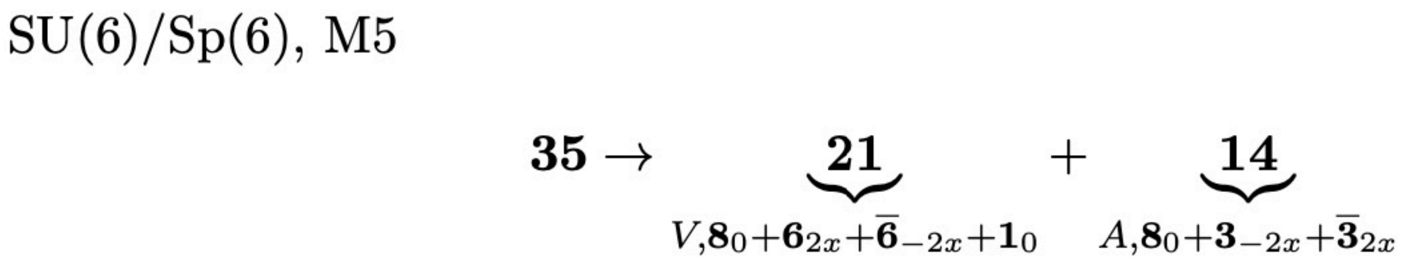
2002.01474



Next: spin-1 resonances

G.C., A.Cornell, A.Deandrea, M.Kunkel, W.Porod
Work in progress

- Spin-1 states from the QCD sector relevant, as they carry QCD charges!



SU(6)/Sp(6), M5

$$\mathbf{35} \to \underbrace{\mathbf{21}}_{V,\mathbf{8}_0+\mathbf{6}_{2x}+\overline{\mathbf{6}}_{-2x}+\mathbf{1}_0} + \underbrace{\mathbf{14}}_{A,\mathbf{8}_0+\mathbf{3}_{-2x}+\overline{\mathbf{3}}_{2x}}$$

- Pair-production can lead to top-rich final states:

$$V_8 \to \pi_8\pi_8\,,\, \pi_3\pi_3^* \;\; (+t\bar{t}, gg, \ldots) \qquad\qquad V_6 \to \pi_8\pi_3^*$$

(Also single-produced)

$$A_8 \to \pi_8\pi_8\pi_8\,,\, \pi_8\pi_3\pi_3^* \qquad\qquad A_3 \to \pi_8\pi_8\pi_3$$

- Classification in progress… stay tuned.

The composite Higgs wilderness

- Light ALPs
- Electroweak pNGBs (2 or 4 tops)
- Coloured scalars (2 or 4 tops)
- Common exotic top partner decays (tops)
- Exotic top partners (more tops)
- Spin-1 resonances (even more tops)
- ...

What if FCC-ee discovers Z > γa?

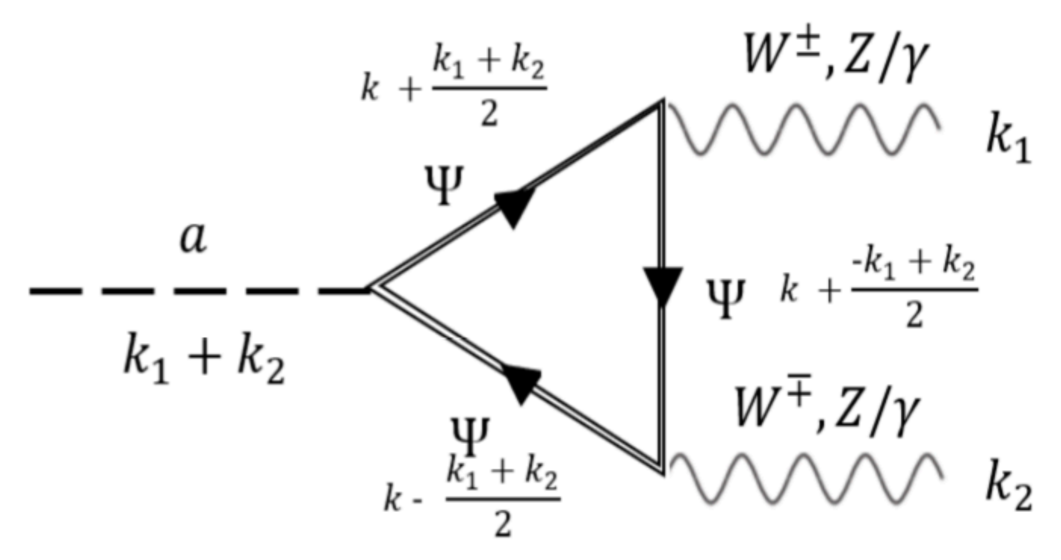
G.C., A.Deandrea, A.Iyer, A.Pinto
2211.00961

- Is it possible to distinguish the composite scenario, from an elementary mock-up model?

$\Phi = H + i\,a$

Singlet scalar

Ψ = doublet + singlet



Triangle loops can mimic the WZW interactions of the composite ALP:

doublet + singlet = photo-phobic case

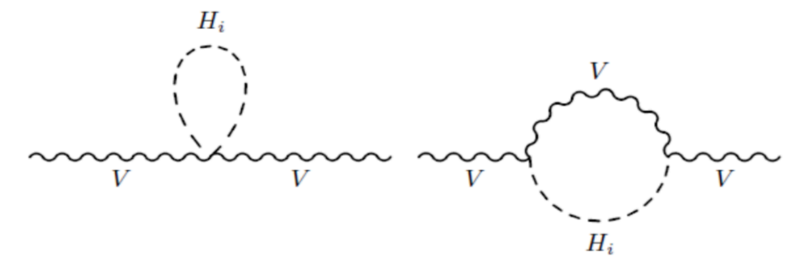
- Note: fermion masses of the order of TeV, potentially discoverable at HL-LHC or FCC-hh (QCD-neutral)

What if FCC-ee discovers $Z \to \gamma a$?

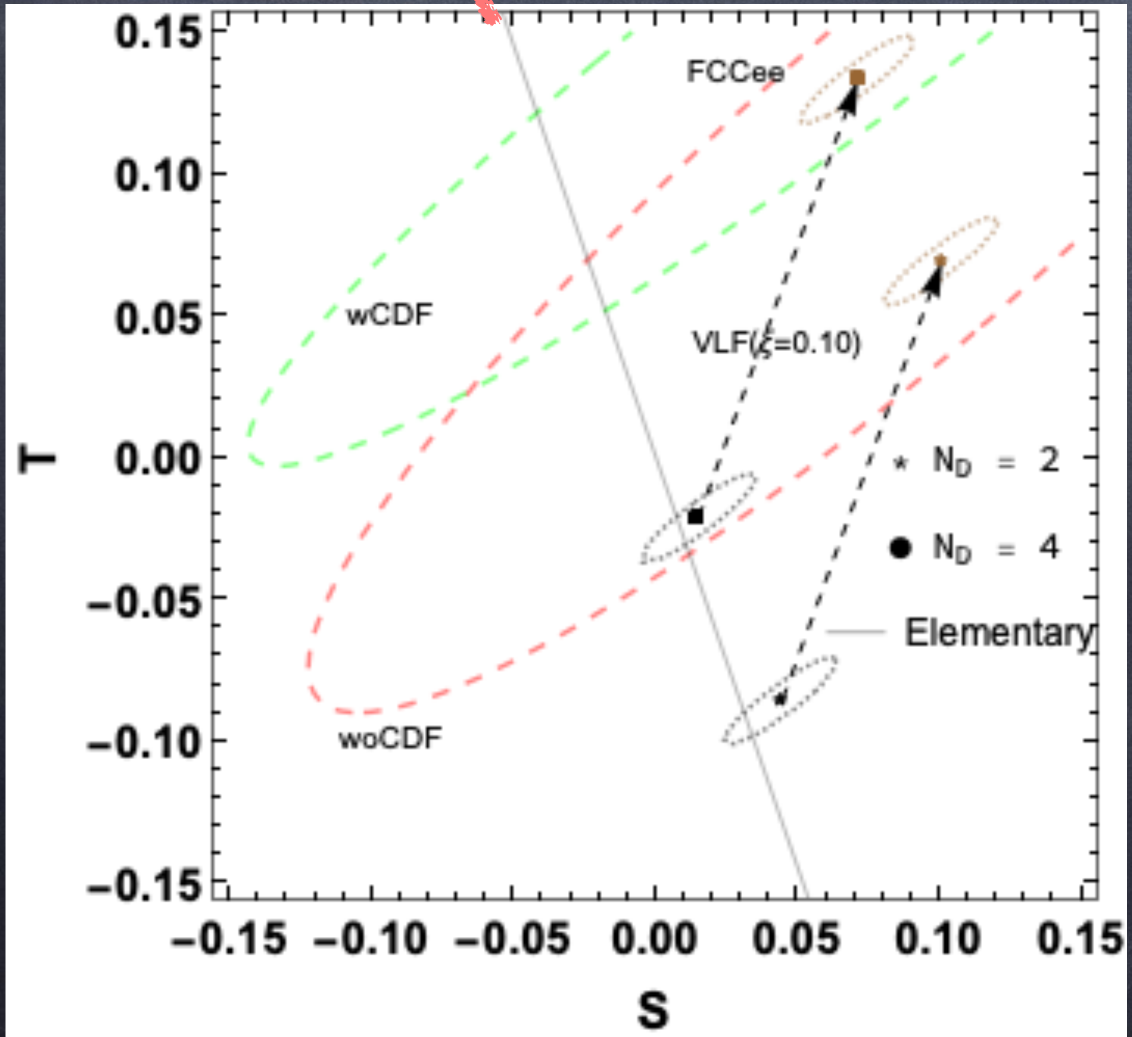
G.C., A.Deandrea, A.Iyer, A.Pinto
2211.00961

- Is it possible to distinguish the composite scenario, from an elementary mock-up model?

EWPT only depend
on H loops



composite case:
see 1502.04718



For fixed BR = 10^-8,
i.e. discovery.

Arrows: naive contribution
of top partner loops.